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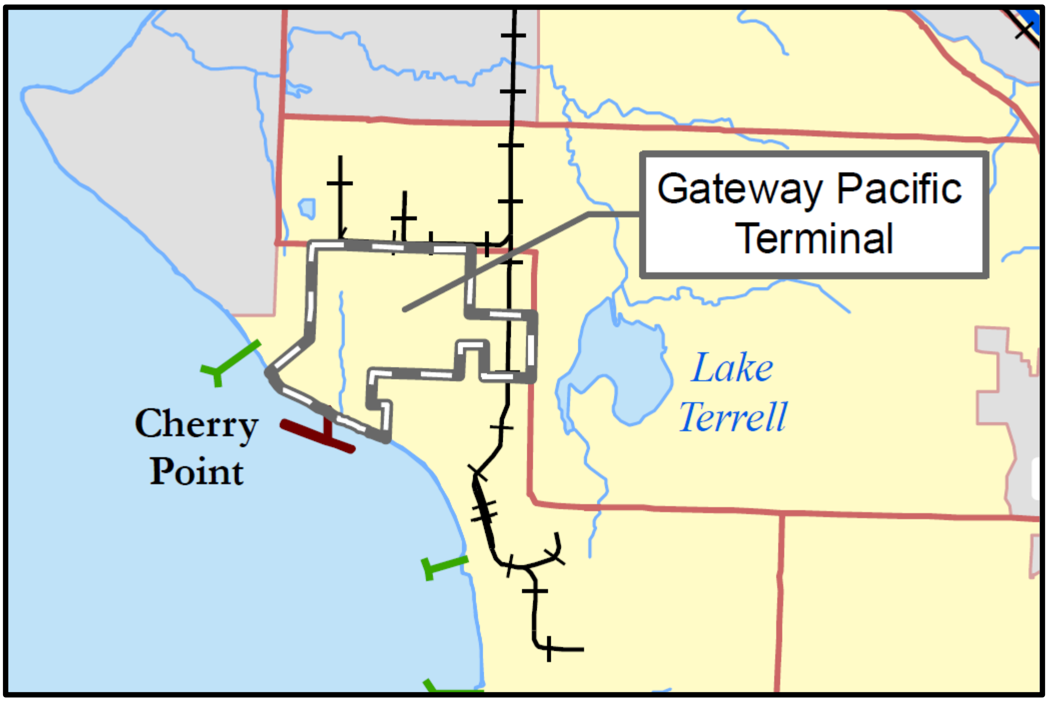
Revision Number 0

Pacific International Terminals Gateway Pacific Terminal

Metocean Study December 2012

3 Dec. 2012



Revision Status

Revision	Date	Description	Author		Approver	
			FirstName LastName	Position Title	FirstName LastName	Position Title
0	3/Dec/2012	For Issue to Client	Sundar Prasad	Senior Specialist	Max Larson	Senior Coastal Engineer

Ausenco

GPT
Gateway Pacific Terminal

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1 Introduction

Ausenco have been engaged by Pacific International Terminals to conduct a study to estimate the long term wave climate statistics at a proposed berth located near Cherry Point, Whatcom County, Washington as shown in Figure 1-1.

Figure 1-1 Location of Cherry Point (Google Earth™ image)

The proposed berth will be situated at approximately 519138 m E, 5411403 m N (UTM Zone 10U) in approximately 22 m chart depth. The water depth at this location will allow Panamax and Capesize bulk carriers to use the berth.

This report describes the methodology used to estimate the operational and extreme wave climate at the proposed berth location. Results for wave statistics are summarised and presented.

1.1 Terminology

In this document, waves are commonly described using three parameters:

- The significant wave height, Hs, is defined as the average height of the highest $1/3^{rd}$ waves in a sea-state;
- The peak period, Tp, is the average time interval between the arrival of successive crests of the most energetic waves, and;
- The peak direction, Dp, is the direction *from* which the most energetic waves arrive and is typically referenced to True North (TN).

2 Data Sources

2.1 Reference Water Levels

Historical water level measurements at Cherry Point, WA are available from the NOAA National Ocean Service (NOS) Station CHYW1 – 9449424. On the basis of data analysed for the 1983-2001 epoch, reference water elevations are provided at the station website and reproduced in Table 2-1.

Table 2-1 Reference water levels at Cherry Point

Datum	Value (m)	Description
MHHW	4.721	Mean Higher-High Water
MHW	4.468	Mean High Water
MTL	3.599	Mean Tide Level
MSL	3.543	Mean Sea Level
MLW	2.729	Mean Low Water
MLLW	1.933	Mean Lower-Low Water (CD)
STND	0	Station Datum
Maximum	5.846	Highest Observed Water Level
Minimum	0.634	Lowest Observed Water Level
HAT	5.282	Highest Astronomical Tide
LAT	0.756	Lowest Astronomical Tide

The data shows that the highest observed water level of 5.846 m, which is expected to be a combination of tide and storm surge, is 3.91 m above the local chart datum (CD = MLLW). Statistical analysis of the measured water levels at Cherry Point indicates that the water level with a 1% annual probability of exceedance is 2.29 m above MSL (3.9 m above chart datum).

An allowance of 1 cm for every year of the terminal's design life should be added to the water levels in Table 2-1 to account for climate change induced sea level rise.

2.2 Waves

An Acoustic Doppler Current Profiler (ADCP) was deployed off Cherry Point at 48.8553° N, 122.7391° W. The ADCP measured water level, current profile, and directional wave spectra from 22 Dec 2011 to 23 Feb 2012. Details of the deployment are given in a report, "Current Profile & Wave Measurements, Gateway Pacific Terminal, Cherry Point, WA, Dec 22 2011 – Feb 23 2012" by ASL Environmental Sciences Inc. dated 27 Feb. 2012.

Figure 2-1 shows the timeseries of significant wave height, Hs, recorded by the ADCP. The largest Hs of 1.7 m was recorded at 1300 hrs PST on 25 Dec. 2011. The peak period, Tp, of the waves at that time was 5.0 sec and the peak wave direction, Dp, was 188 deg. Figure 2-2 shows the directional wave spectrum during the peak of the storm. Winds recorded at the Cherry Point station reached 17.6 m/s (34 knots) at this time and were from 216 deg TN.

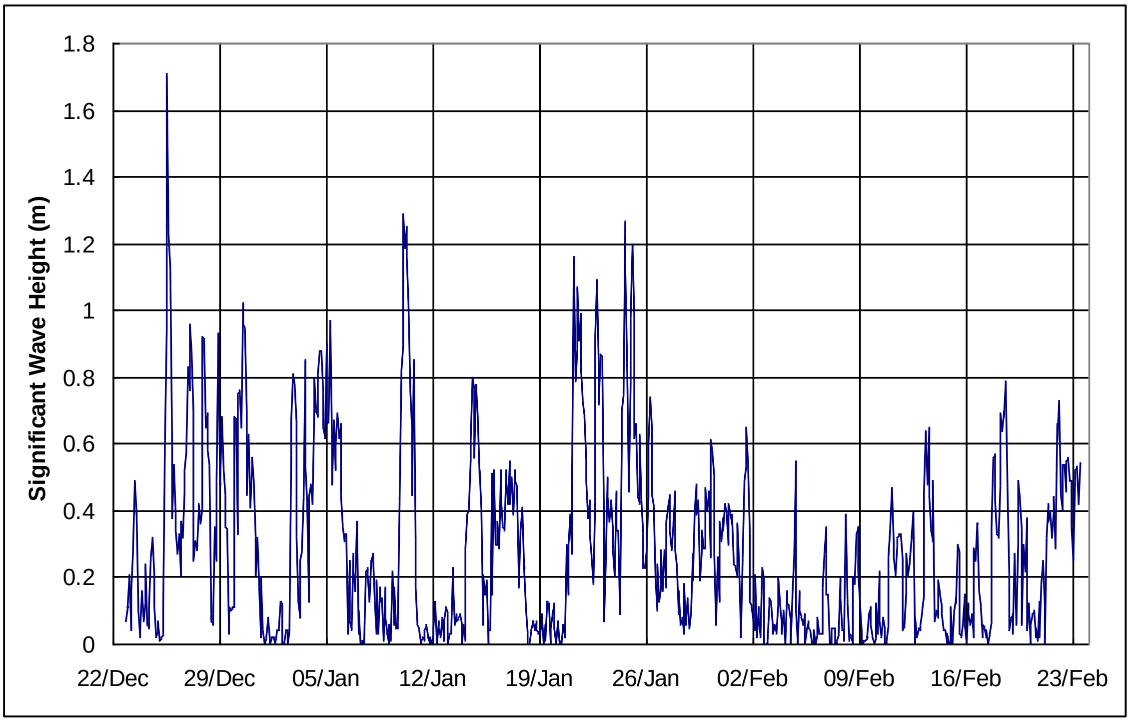

Figure 2-1 Timeseries of measured wave height at Cherry Point (Dec. 2011 to Feb. 2012)

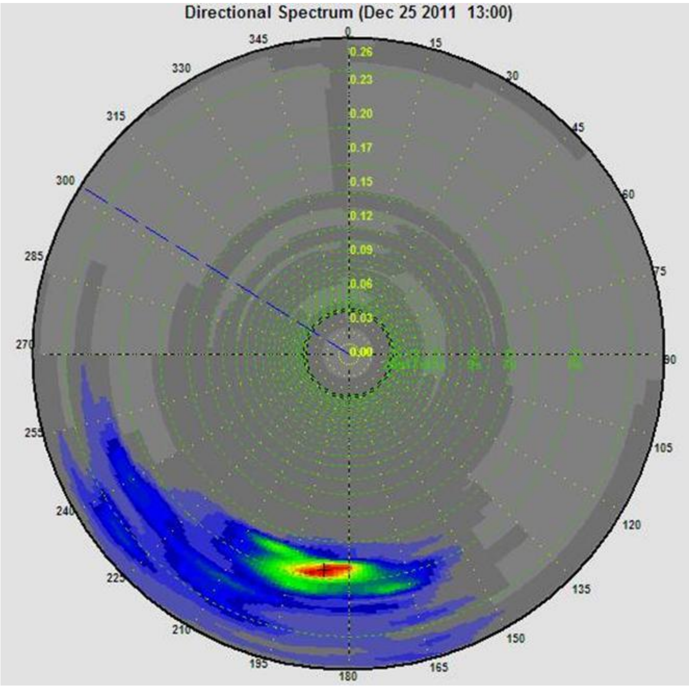

Figure 2-2 Wave spectrum in 25 Dec. 2011 storm (Hs = 1.7 m, Tp = 5.0 sec, Dp = 188 deg)

Two other events were recorded during the measurement program during which Hs reached a maximum value of 1.3 m – one on 10 Jan. 2012 and the other on 24 Jan. 2012. The wave spectrum at the peak of the 10 Jan. event is shown in Figure 2-3. The associated value of Tp and Dp were 5.4 sec and 266 deg respectively. Winds recorded at the Cherry Point station (described in Section 2.4) reached 15.5 m/s (30 knots) at this time and were from 300 deg TN.

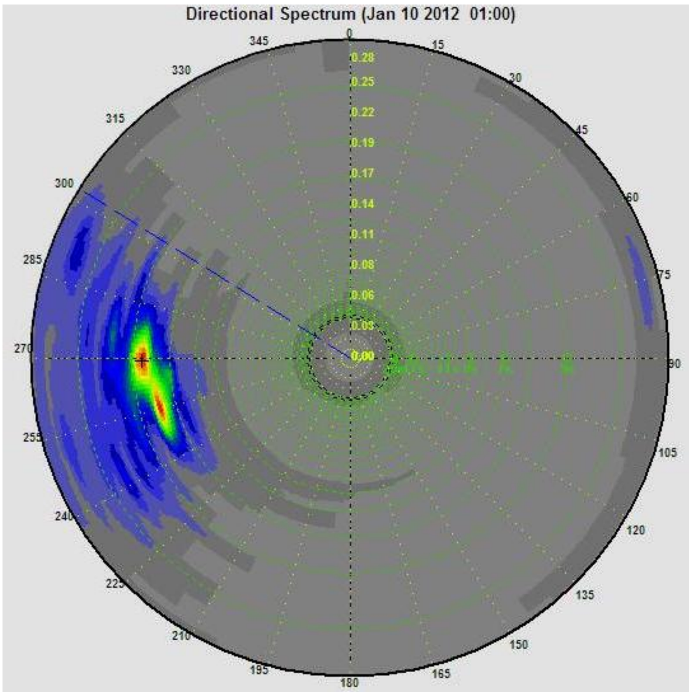

Figure 2-3 Wave spectrum in 10 Jan. 2012 storm (Hs = 1.3 m, Tp = 5.4 sec, Dp = 266 deg)

Figure 2-4 shows the probability of exceedance for the significant wave height measured by the ADCP. In general, wave heights are low, with approximately 2% of the measured waves exceeding a significant height of 1.0 m. Calm conditions, defined by significant wave heights less than 0.1 m and/or peak wave periods less than 1.0 sec, are seen to occur approximately 33% of the time during the measurement period.

Figure 2-5 shows the histogram of peak wave period recorded by the ADCP. The dominant role played by local wind generated seas is evident in the figure, which shows that the most commonly occurring wave periods are between 2 sec and 4 sec. These waves are typically not expected to induce significant motions or mooring system forces for vessels at the proposed berth.

The directional distribution of the measured waves is shown in Figure 2-6. Waves at Cherry Point are almost entirely incident from the SW quadrant due to the orientation of the coastline near the project site. Approximately 22% of the waves are southerly, while 14% are from the west. There is more frequent incidence of higher waves (Hs > 0.6 m) from the south.

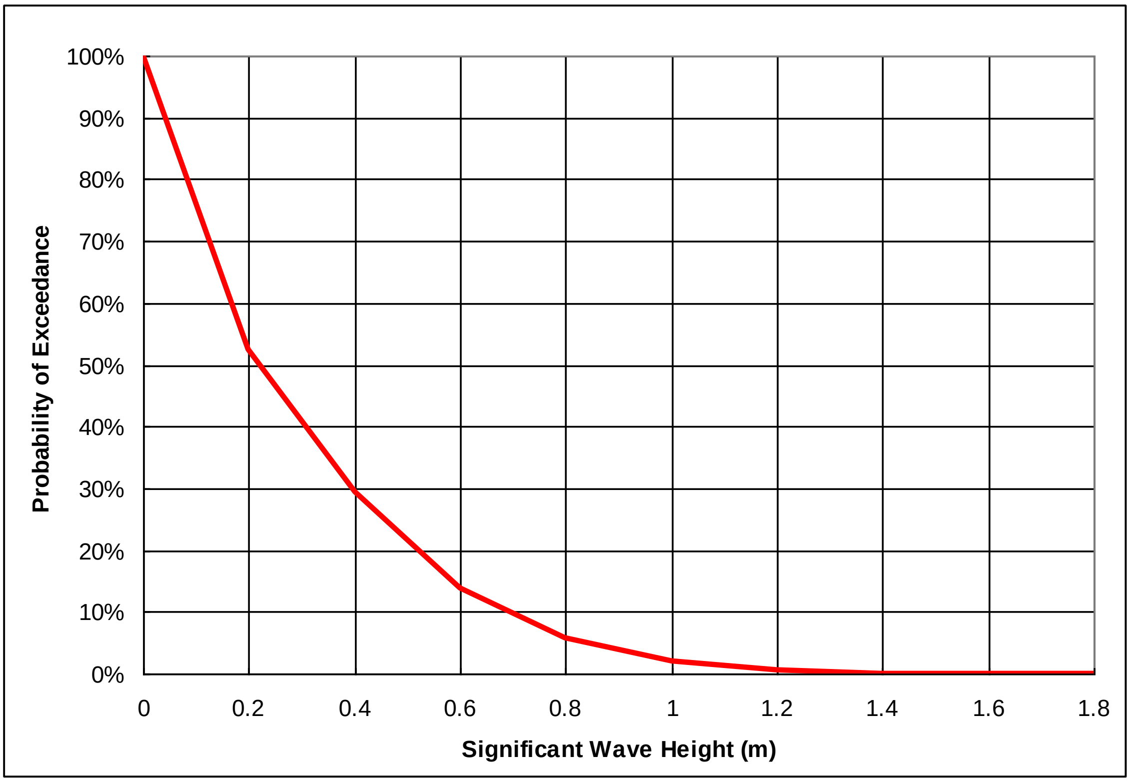

Figure 2-4 Statistics of measured wave height at Cherry Point (Dec. 2011 – Feb. 2012)

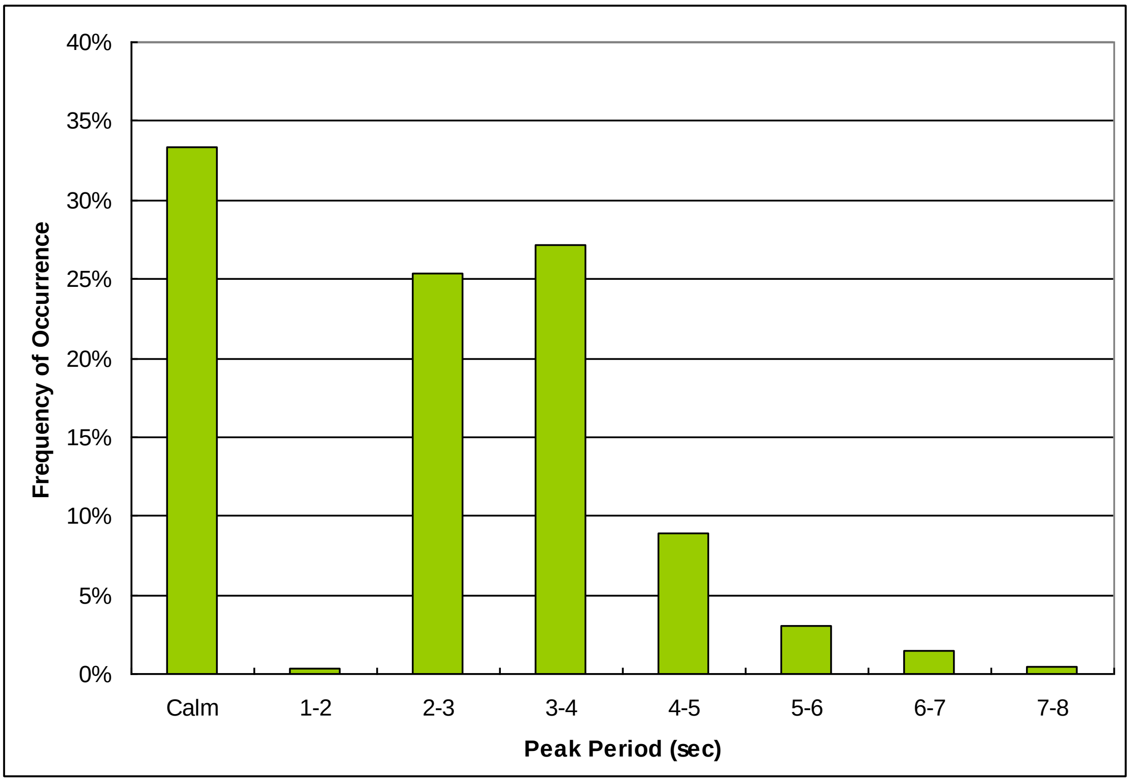

Figure 2-5 Statistics of measured wave period at Cherry Point (Dec. 2011 – Feb. 2012)

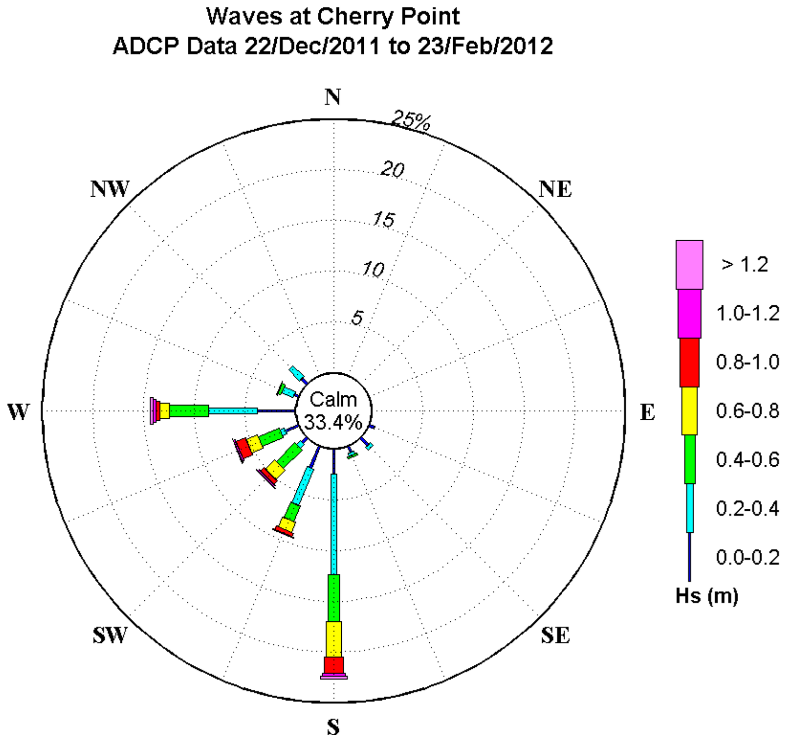

Figure 2-6 Wave rose for Cherry Point based on measurements (Dec. 2011 – Feb. 2012)

2.3 Currents

The ADCP also recorded the water depth and current profiles over the water column. Figure 2-7 shows the measured water level relative to the mean water level (MWL = 22.58 m above the ADCP pressure sensor at the measurement location) during a spring tide cycle in late Jan. 2012. The maximum tide elevation during the measurement period was 1.65 m above MWL.

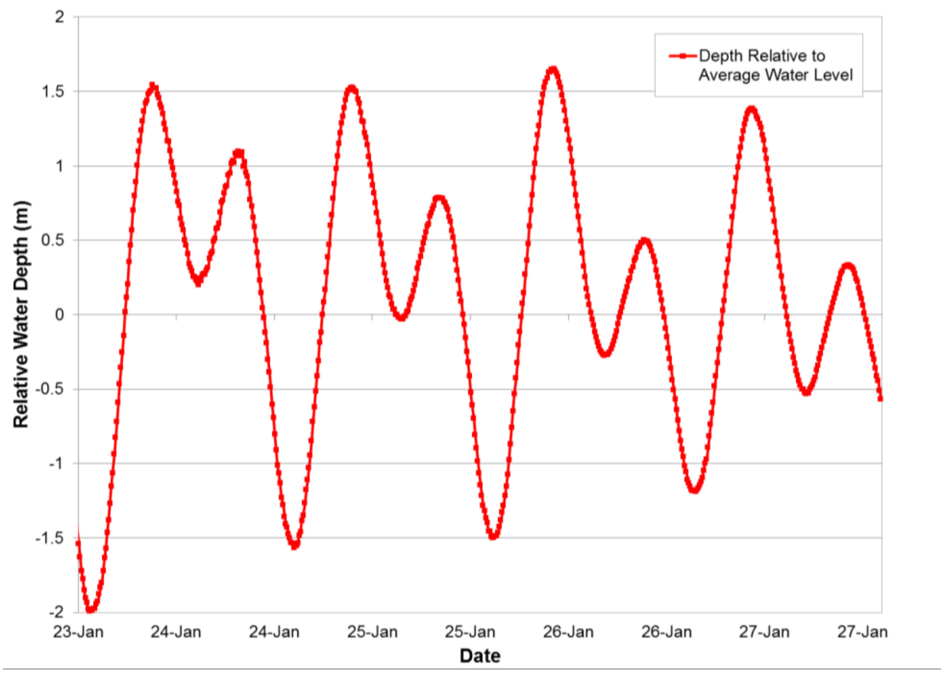

Figure 2-7 Water level variation during spring tide at Cherry Point relative to MWL

The currents observed by the ADCP near the water surface (18.7 m above the seabed), mid depth (10.7 m above the seabed), and near the bottom (2.7 m above the seabed) are plotted in Figure 2-8, Figure 2-9 and Figure 2-10 respectively.

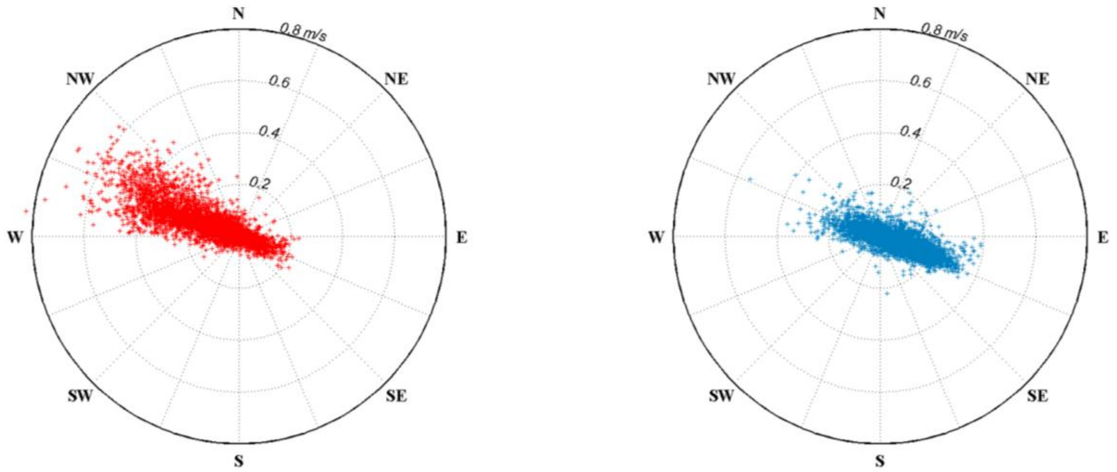

Figure 2-8 Near-surface current during flood (red) and ebb (blue) phases

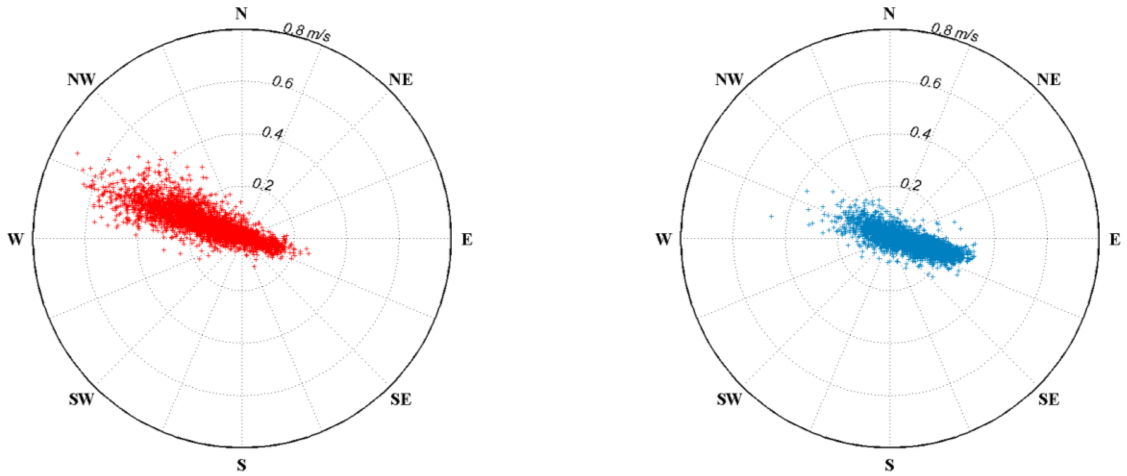

Figure 2-9 Mid-depth current during flood (red) and ebb (blue) phases

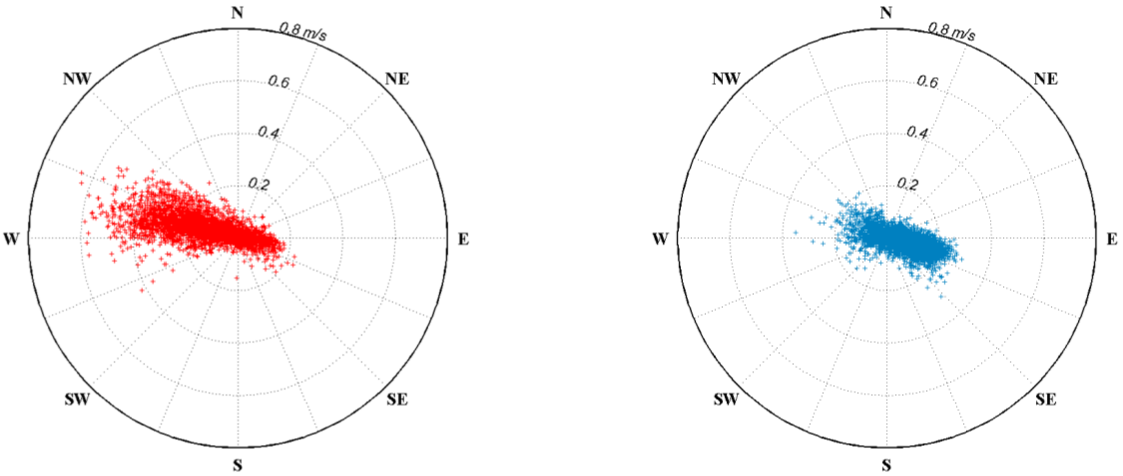

Figure 2-10 Near-bottom current during flood (red) and ebb (blue) phases

At all depths, peak current speeds during the flood phase (rising water level) are seen to be almost double those during the ebb (falling water level). Currents mainly flow towards the WNW during the flood and towards ESE during the ebb. The near-surface flood current typically does not exceed 0.7 m/s (1.4 knots).

2.4 Winds

Wind measurements in the vicinity of the project site are available from two sources: NOAA's NOS station CHYW1 – 9449424 at Cherry Point, and the Saturna Island CS station operated by Environment Canada. These stations are separated by a distance of 22.8 km and are shown in Figure 2-11.

Wind data (speed and direction) from the Cherry Point station is available for a relatively short period from September 2008 to September 2012 at six minute intervals. In comparison, The Saturna Island hourly averaged wind data covers the period from March 1994 to October 2012. Both stations are presently operational.

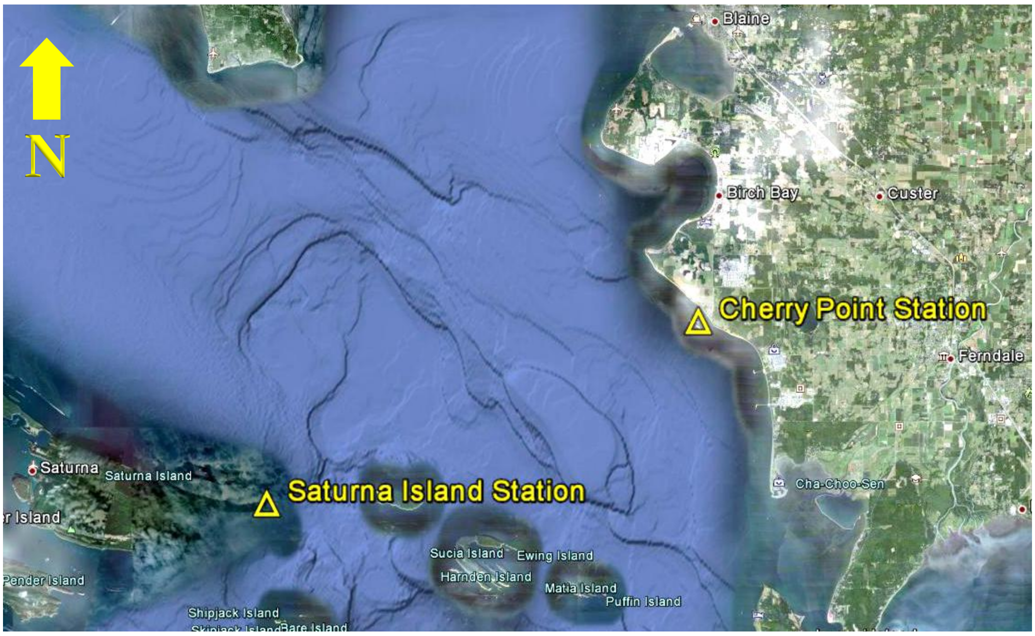

Figure 2-11 Cherry Point and Saturna Island wind stations (Google Earth™ image)

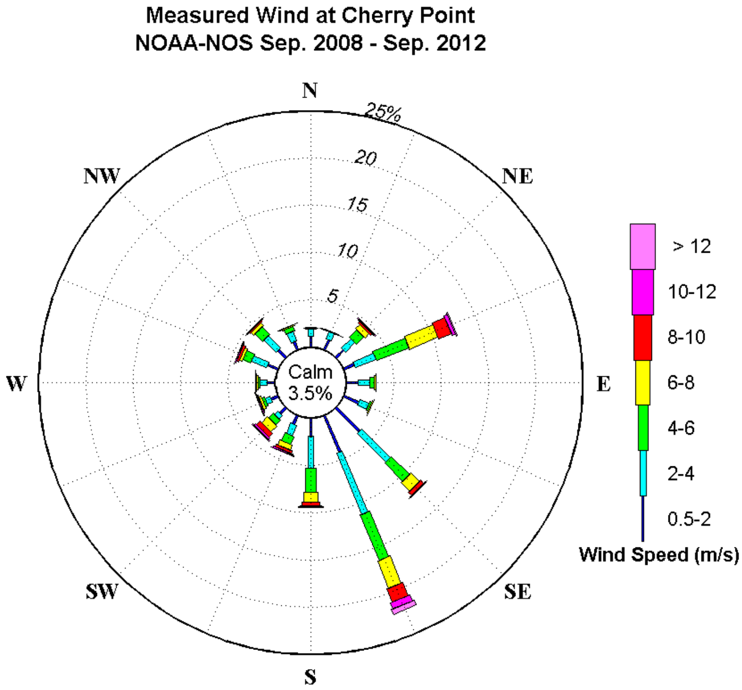

Figure 2-12 Wind rose for Cherry Point

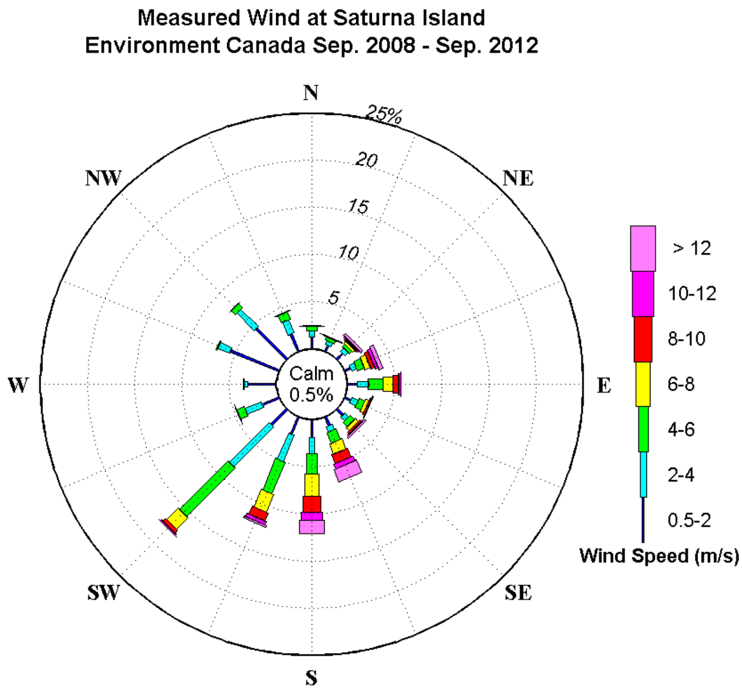

Figure 2-13 Wind rose for Saturna Island (overlap period with Cherry Point data only)

Figure 2-14 shows the wind speed exceedance statistics at Cherry Point and Saturna Island. While the statistics are quite similar at the two stations for the lower 90% of the measurements (up to approximately 8 m/s), the highest 10% of the datasets show marked divergence with stronger winds at Saturna Island occurring more frequently. The comparison between the last 4 years of data with the full 17+ years at Saturna Island shows no discernible change in wind behaviour.

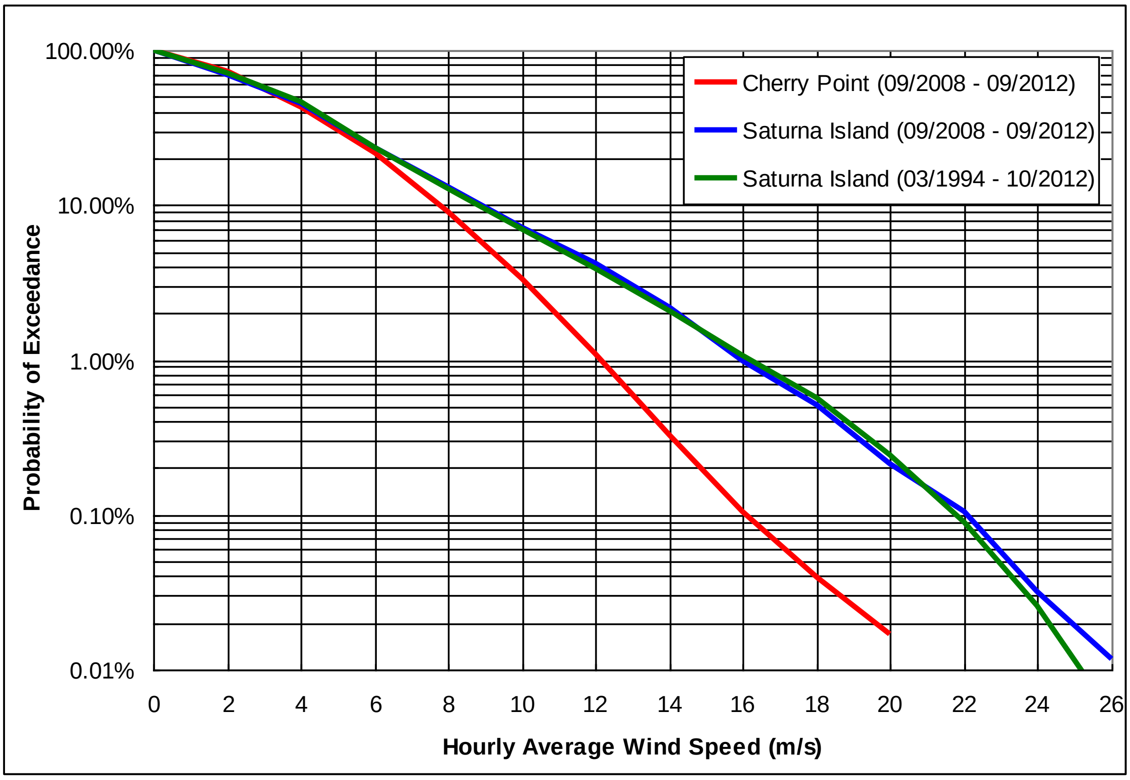

Figure 2-14 Wind speed exceedance plot for Saturna Island and Cherry Point

Further evaluation of the directional characteristics of the wind data from the two stations has been carried out by sorting winds into four direction sectors, with each 90 deg wide sector centred along a cardinal compass direction. The frequency of wind occurrence in each sector is compared in Table 2-2.

Table 2-2 Frequency of wind occurrence (hourly observations)

Sector	Cherry Point		Saturna Island	
	Obs.	%	Obs.	%
N	3709	11%	4692	14%
E	9095	27%	5296	16%
S	16264	48%	14533	43%
W	4810	14%	9357	28%
Total	33878	-	33878	-

While occurrence frequencies of winds from the N and S quadrants are similar at both stations, there is a westerly bias at Saturna Island in comparison to a corresponding easterly bias at Cherry Point. The wave measurements at the project site (Figure 2-6) show that the dominant wave directions lie in the SW quadrant, which is qualitatively matched more closely by the directional distribution of wind at Saturna Island.

It is instructive to compare the wind speed distribution in each quadrant at both stations. Figure 2-15 shows quantile-quantile (QQ) plots of wind speed for each direction sector. The QQ plots show that wind speeds at Saturna Island are higher than those at Cherry Point for the N, E, and S quadrants, but lower for the W quadrant (even though the frequency of winds from this sector is markedly higher at Saturna Island). This may be due to topographic sheltering for westerly winds at the Saturna Island anemometer which is not present at Cherry Point. The wind measurements indicate significant spatial variability and a complex wind regime in the area of interest. Consequently, accurate wave hindcasting from wind data presents a bigger challenge in comparison to sites where the wind exhibits more spatial uniformity.

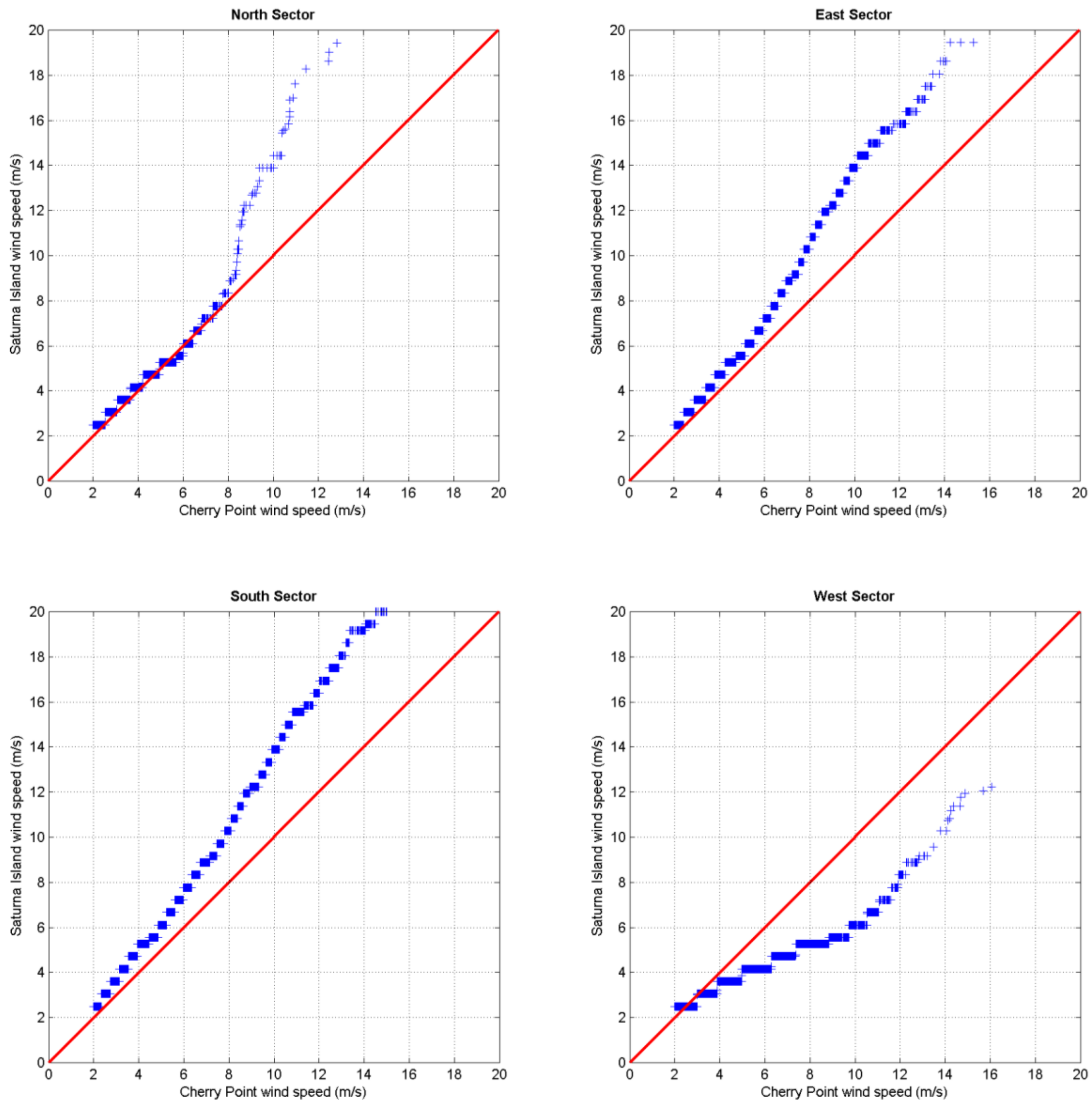

Figure 2-15 Sector-wise QQ plots of Cherry Point and Saturna Island wind speed

3 Wave Hindcast

3.1 General

Waves at the proposed Gateway Pacific terminal are expected to be generated by local wind activity only. The dense cluster of islands to the southwest of the project site and the orientation of the Juan de Fuca Strait blocks Pacific Ocean swell that arrives on the west coast of Vancouver Island from propagating to the berth location at Cherry Point.

The numerical prediction of wave climate at the proposed berth is described in this section. Two methods have been used to estimate waves generated by winds in the Strait of Georgia.

The primary approach is based on the Sverdrup, Munk and Bretschneider (SMB) equations described in the US Army Corps of Engineers Shore Protection Manual. The SMB equations use inputs such as fetch length, wind speed and water depth to arrive at estimates of wave parameters such as significant wave height and peak period. These empirically derived equations benefit from rapid computation times due to the relatively simple formulation.

The predictions of the SMB model have been compared with results from the more sophisticated SWAN wave model developed by the Technical University of Delft (Netherlands). SWAN uses a significantly more detailed description of the bathymetry in the wave generation area and includes complex physical processes such as bottom friction, wave refraction, and nonlinear wave-wave interactions which are not included in the SMB equations. The trade-off is the markedly longer model run times in comparison to the SMB model.

In the present study, the SMB model has been used to estimate the long-term wave climate at the proposed terminal, while the SWAN model has been used to validate selected predictions of the SMB model.

3.2 Bathymetry

The bathymetry of the Strait of Georgia is referenced from nautical charts and survey data. The depth values reported correspond to Canadian chart datum, which is defined as the Lowest Normal Tide (LNT) in Canadian Waters. Values from US sources which use Mean Lower-Low Water as a datum have been converted to the Canadian standard. All SWAN simulations in the present study have been run with water depths referenced to mean sea level.

3.3 Wave Models

3.3.1 SMB Model

The SMB equations have been used to perform the wave hindcast, to take advantage of the rapid computation that this method offers. Wind speed, fetch length and average depth are defined as inputs to the SMB model. As noted before, the SMB approach does not account for wave refraction. This is not expected to be an issue as the relatively small fetches in the area of interest imply that wind generated waves will have periods that are relatively small – the ADCP measurements show that over 90% of the waves have peak periods less than 5 sec. These waves have deep water wave lengths less than 40 m and will thus not begin to refract until they reach water depths less than 20 m.

A sketch for the fetch lengths centred on a sixteen point compass is shown in Figure 3-1. The selected fetch for a given wind direction, e.g. 270 deg, is the longest available fetch over a ±10 deg sector centred on that direction. The sixteen fetches at the proposed berth location are shown in red, and their details are given in Table 3-1. The fetch lengths have been estimated using Google Earth and the average depth calculated from the bathymetry data.

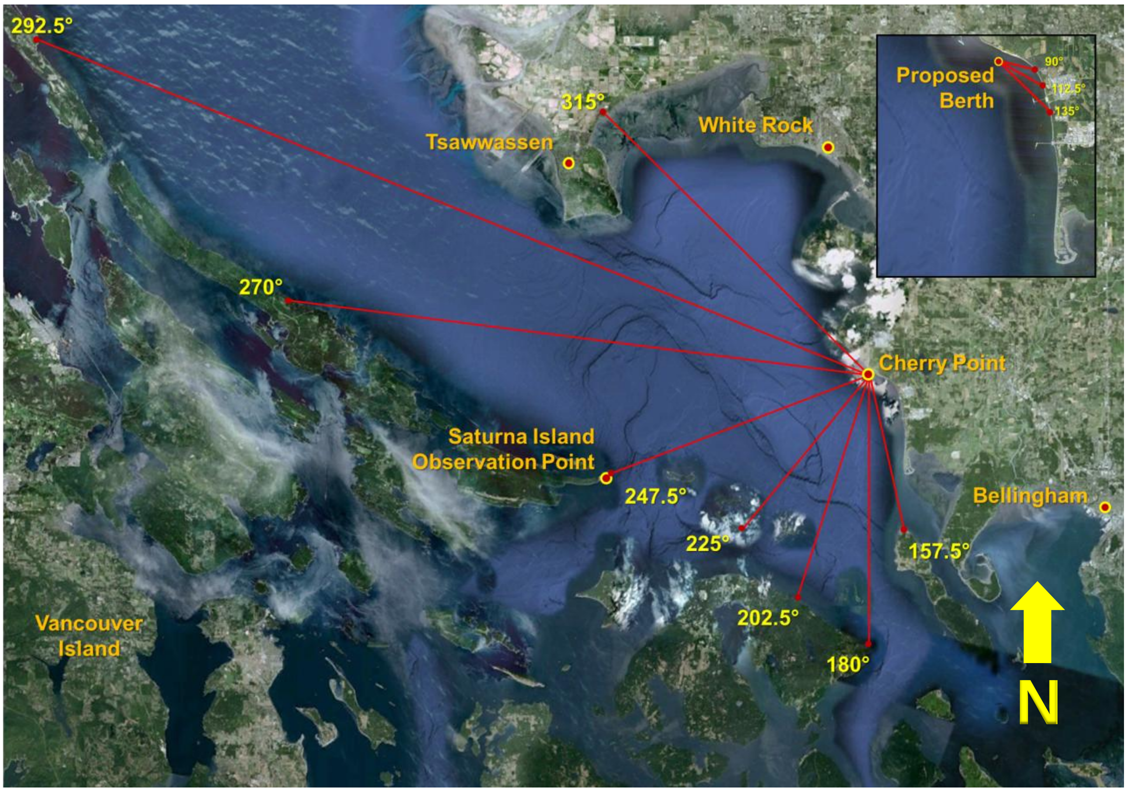

Figure 3-1 Available fetch lengths at the proposed berth location (Google Earth™ image)

Table 3-1 Fetch details (origin at 519138 m E, 5411403 m N)

Direction (deg)	Length (km)	Avg. Depth (m)
0	0	0
22.5	0	0
45	0	0
67.5	0	0
90	1.4	10
112.5	1.9	10
135	3.4	13
157.5	11.9	14
180	21.2	50
202.5	18.6	58
225	15	59
247.5	22.5	124
270	50	132
292.5	73	147
315	31	17
337.5	0	0

3.3.2 SWAN Model

A detailed bathymetry grid encompassing the Strait of Georgia and the eastern end of the Strait of Juan de Fuca has been assembled using data from surveys and nautical charts for the SWAN model. Figure 3-2 shows the extents of the model domain. A grid resolution of 500 m has been used for the present study.

The SWAN model has been run in both non-stationary and stationary modes. In the former, a time-varying wind speed and direction is applied over the model domain, while a constant wind speed and direction is defined in the latter case. Spatial variability in the wind field has not been investigated in the present study. No waves are applied at the open ocean boundary as any Pacific Ocean swell propagating through the Strait of Juan de Fuca is expected to be blocked by the island cluster to the southwest of Cherry Point.

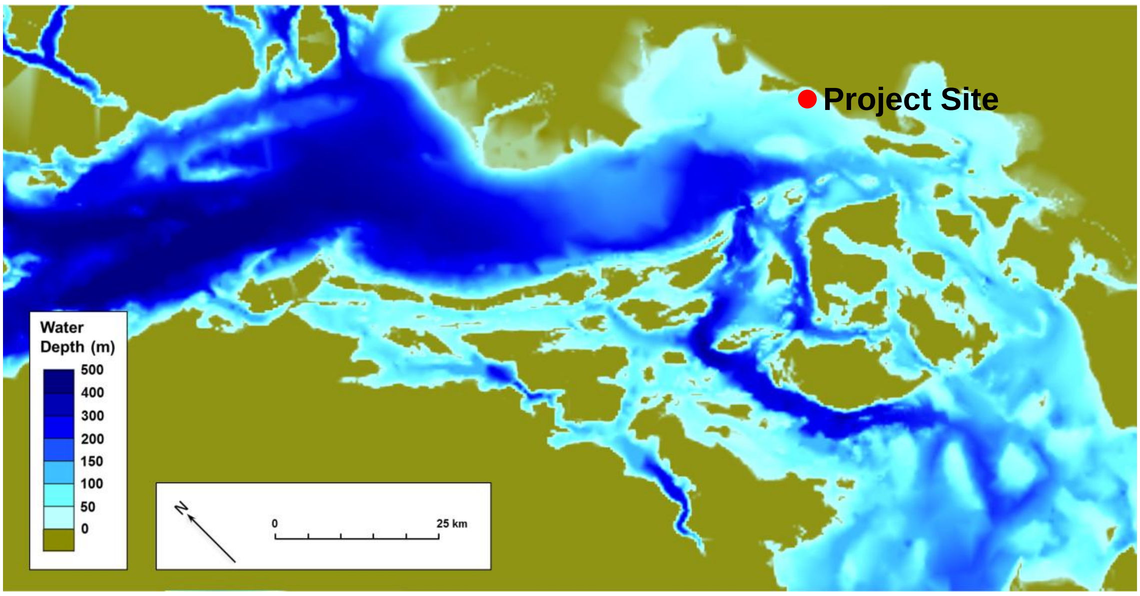

Figure 3-2 SWAN computational domain bathymetry

3.3.3 Wave Model Validation

It is of interest to first examine the estimates of wave conditions from the SMB and non-stationary SWAN simulations using wind data measured at Saturna Island for the period when the ADCP measurements of waves at the project site are available.

Figure 3-3, Figure 3-4, and Figure 3-5 show the measured significant wave height, peak period, and peak direction respectively compared with computed values from the SWAN and SMB models for the period between 25 Dec. 2011 and 4 Jan. 2012.

The comparisons show that in general, the wave models marginally overestimate the wave height at the measurement location. However, the SWAN model does not match the wave height during the peak of the 25 Dec. storm (see Section 2.2), which is better captured by the SMB model. It is noted that the precise reason for this discrepancy is only of academic interest as the more conservative SMB model predictions have been used to produce the estimates of operational and extreme wave conditions at the project site.

A wave event during 2 Jan. 2012 that was measured by the ADCP as being from south is seen to be severely overestimated by the SMB method, and is likely due to weaker winds over the fetch to the south of Cherry Point than those measured at Saturna Island at that time. This tendency of the SMB model to generally overestimate the height of southerly waves is corrected (albeit with some conservatism still retained to account for uncertainty in the wind definition) as described in Section 3.4.

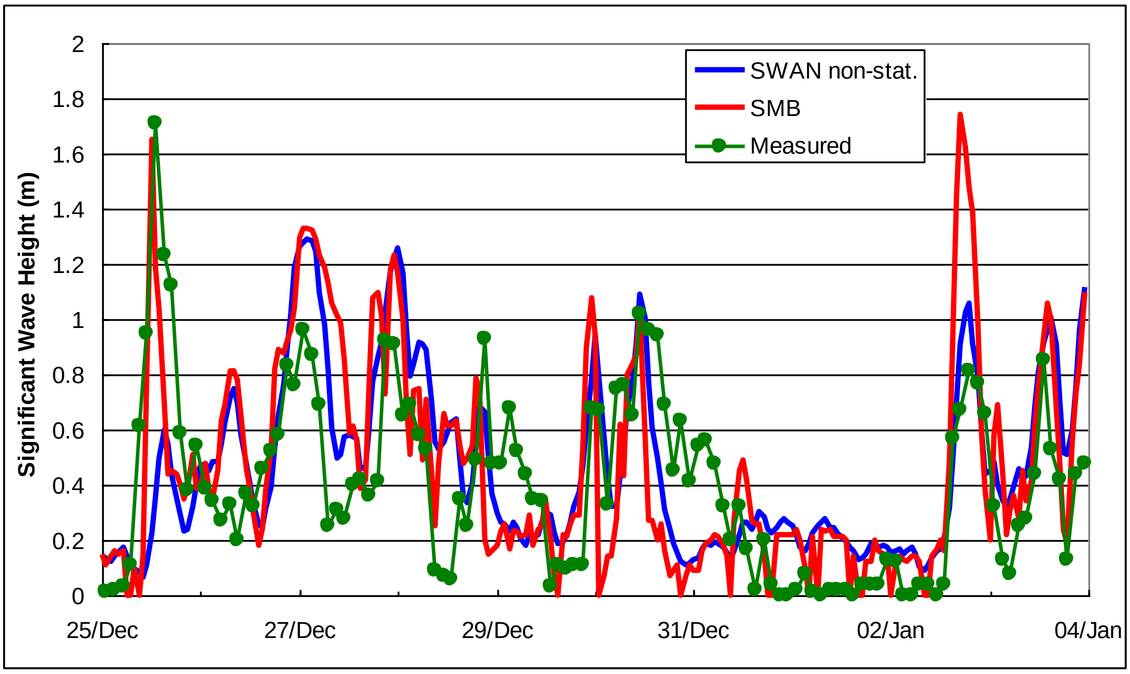

Figure 3-3 Comparison of wave height measurements with numerical model output

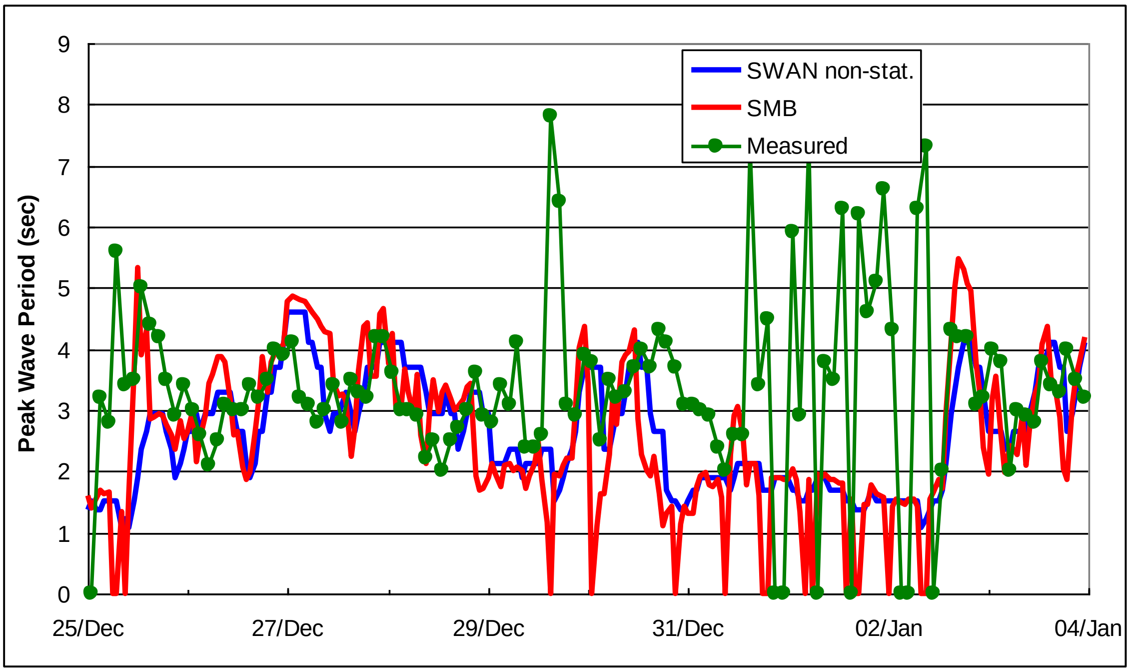

Figure 3-4 Comparison of wave period measurements with numerical model output

The results also show reasonably good agreement between the measured and modelled peak wave period and direction. Note that the estimates of wave parameters such as peak period and peak direction from the ADCP measurements during periods of low wave activity (e.g. 1st to 2nd Jan.) tend to be affected by electronic and environmental noise and are less reliable.

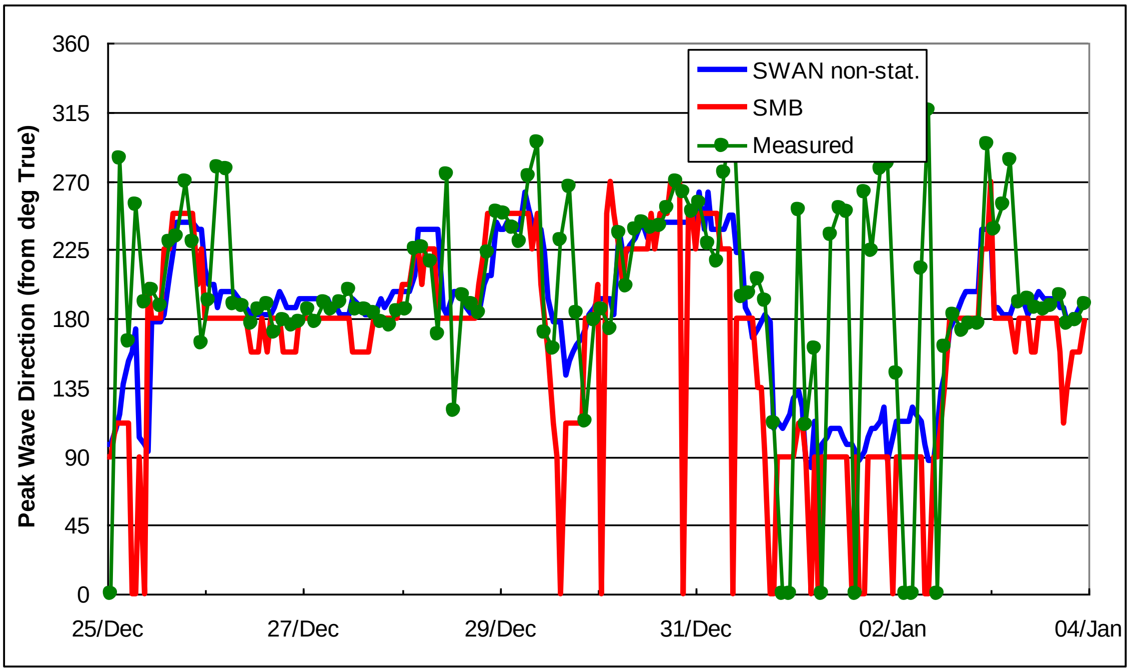

Figure 3-5 Comparison of wave direction measurements with numerical model output

In addition to the non-stationary case described above, the SWAN model has been run in stationary mode (steady wind speed and direction) for two wave events measured by the ADCP on 25 Dec 2011 and 10 Jan 2012. The first represents a typical southerly storm event at Cherry Point, and the second was generated by westerly winds.

The wind speed and direction used for the stationary SWAN simulations are estimated by averaging the measured wind speed at Saturna Island (for the Dec. 25th storm this yields a 13.7 m/s wind from 191 deg), and at Cherry Point (for the Jan. 10th storm this yields a 11.7 m/s wind from 290 deg) over a 3-hour period during the peak of each storm. It is noted that wind data from Cherry Point has been used as input to the wave model as the Saturna Island anemometer did not record *any* westerly winds of significance during the Jan. 10th event. The results of the simulations are summarised in Table 3-2.

Results from a non-stationary SWAN run using winds measured at Cherry Point during the Jan. 10th storm have also been presented in the table for comparison.

In general, the storm simulation results support the observations made above. The SMB model generally yields good comparison with the measured waves for the Dec. 25th event, but severely overestimates the wave height during the Jan. 10th storm. The stationary SWAN models yield closer agreement with the measurements in comparison to the non-stationary runs.

The variations between model and measurements are likely due to the simplified approach used in the present study when defining the input winds in the wave model. Winter winds in the southern Georgia Strait have a different directional distribution on the east side of the strait than the west, and exhibit a significant level of spatial and temporal variability that cannot be captured on the basis of measurements at Cherry Point and Saturna Island alone.

Table 3-2 Comparison between measurements and wave models for two storm events

Storm Date/Time	Wave Parameter	Measured	SMB	SWAN Stat.	SWAN Non-stat.
25 Dec. 2011 13:00 PST	Hs (m)	1.71	1.65	1.36	0.60
	Tp (sec)	5.0	5.3	4.6	3.0
	Dp (deg)	188	180	193	208
10 Jan. 2012 01:00 PST	Hs (m)	1.29	1.82	1.22	1.14
	Tp (sec)	5.4	5.8	5.1	4.1
	Dp (deg)	266	292	273	244

The plots shown in Figure 3-6 and Figure 3-7 show the variation in wave height over the southern part of the SWAN computational grid for the two stationary runs for the Dec. 25th and Jan. 10th events respectively.

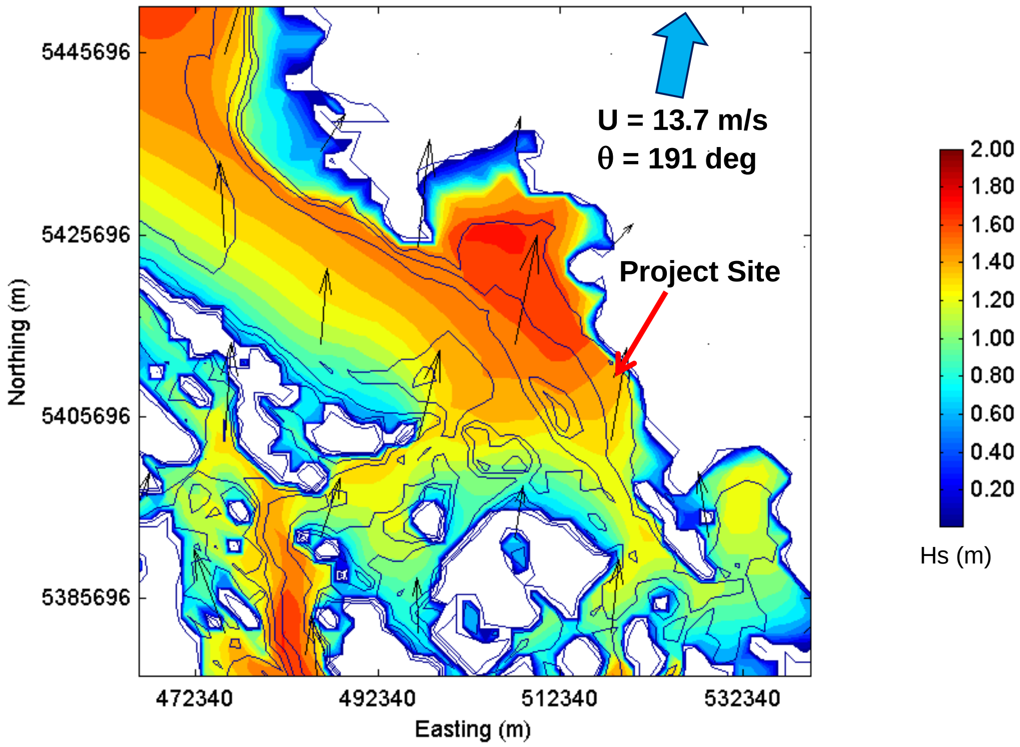

Figure 3-6 SWAN stationary run significant wave height map for the 25 Dec. 2011 storm

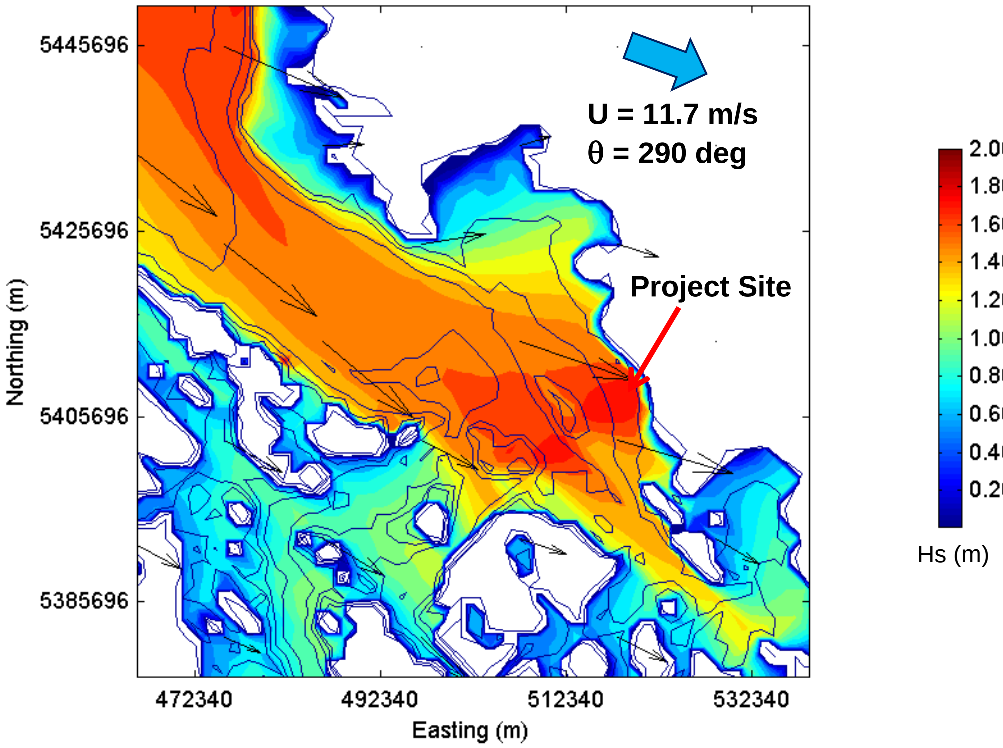

Figure 3-7 SWAN stationary run significant wave height map for the 10 Jan. 2012 storm

3.4 Wave Model Tuning

The long-term wave hindcast for the proposed Gateway Pacific terminal has been produced using the SMB model. Due to the significantly longer record of measured wind data available from the Saturna Island station (Mar. 1994 to present day with approximately 11.8 months of missing data distributed over multiple gaps in the record) in comparison to the wind measurements at Cherry Point (Sep. 2008 to present day with no major data gaps), the former wind dataset has been used as input to the SMB model.

The waves estimated by the SMB model using the Saturna Island winds have first been compared to the wave measurements at Cherry Point for the period between 22 Dec. 2011 and 23 Feb. 2012. Figure 3-8 shows a QQ plot of measured versus hindcast waves from the south sector. The SMB model tends to overestimate the wave height when compared with the measurements. In contrast, the SMB model significantly underestimates wave heights from the west when compared with measurements as seen in Figure 3-9, which is likely due to lower wind speeds being reported by the Saturna Island instrument than those actually occurring over open water (see Section 2.4 for additional information on this issue). Moreover, the frequency of westerly waves is somewhat higher in the measured data.

Waves at Cherry Point are predominantly from the south sector (between 112 and 240 deg), and therefore the difference in magnitude and frequency of occurrence between measured and hindcast westerly waves has not been further investigated in the present study. The wind roses in Figure 2-12 and Figure 2-13 show that there is a higher percentage of westerly winds measured at Saturna Island in comparison to Cherry Point, and therefore westerly waves are represented in the SMB hindcast, albeit with an accuracy lesser than that for the southerly and southwesterly waves.

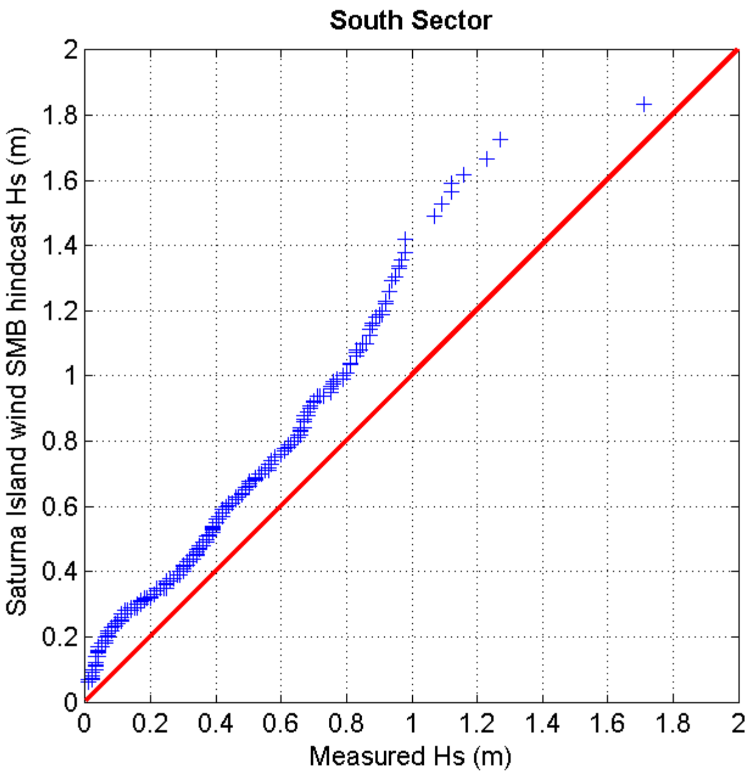

Figure 3-8 QQ plot of measured versus SMB model wave height (112 deg to 240 deg)

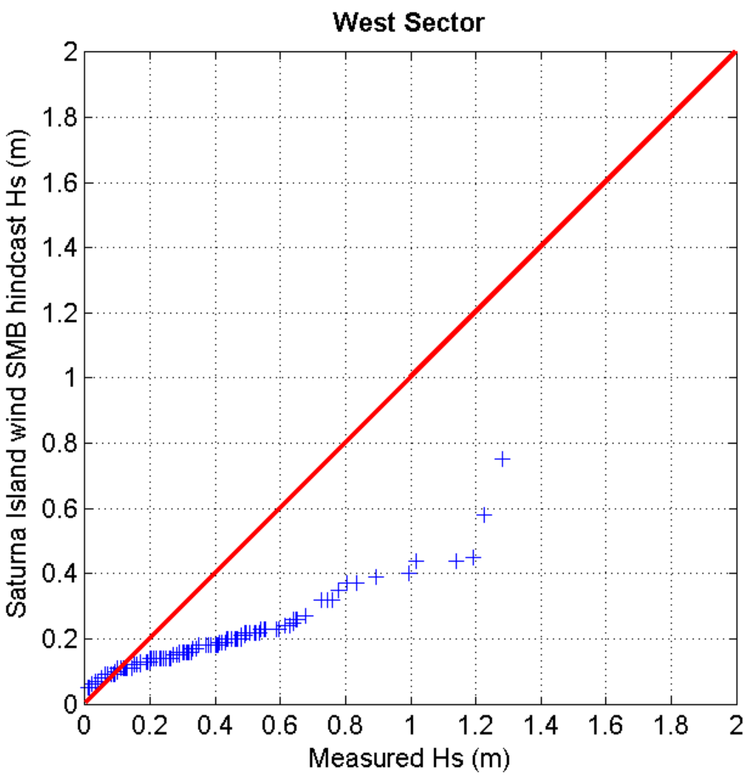

Figure 3-9 QQ plot of measured versus SMB model wave height (241 deg to 315 deg)

Based on the above QQ plot comparisons, the SMB wave hindcast using Saturna Island winds has been modified as follows:

- Hs adjusted = 0.8 x Hs hindcast for waves with directions from 112 to 240 deg;
- Hs adjusted = 1.5 x Hs hindcast for waves with directions from 241 deg to 315 deg;
- Hs adjusted = Hs hindcast for all other wave directions.

Figure 3-10 shows the QQ plot for the combined south and west sector waves after the above adjustments are applied to the hindcast data. The hindcast wave heights are seen to be marginally conservative in comparison with the measurements. This has been retained to allow for the uncertainty in westerly wave estimates using the Saturna Island wind data.

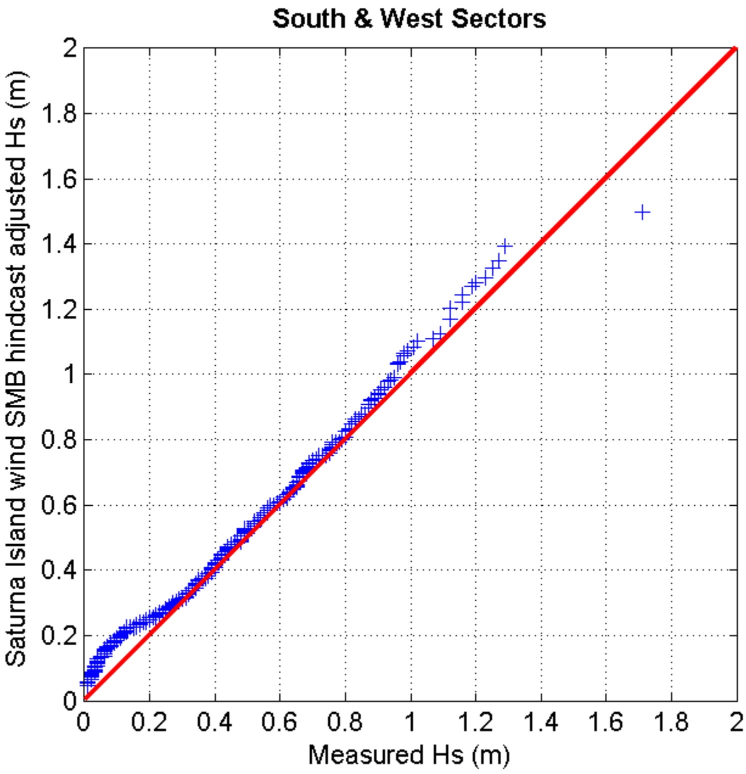

Figure 3-10 QQ plot of measured versus adjusted SMB model wave height (112 deg to 315 deg)

Comparisons of the adjusted hindcast wave height, peak period, and wave direction with the measured waves are shown in Figure 3-11, Figure 3-12, and Figure 3-13 respectively. For clarity, and to reject noisy data from the measurements, only records with significant wave height greater than 0.20 m have been retained in the figures. The plots show that the adjusted hindcast produces a reasonably good match with the measurements, especially for southerly and southwesterly wave events.

A notable exception is the event of 10 Jan. 2012, where westerly waves with Hs of up to 1.3 m were measured, but not predicted in the hindcast due to an absence of suitably high westerly wind speeds in the Saturna Island wind data. A smaller magnitude west-northwesterly event on 13 Feb. 2012 is also not predicted well by the hindcast.

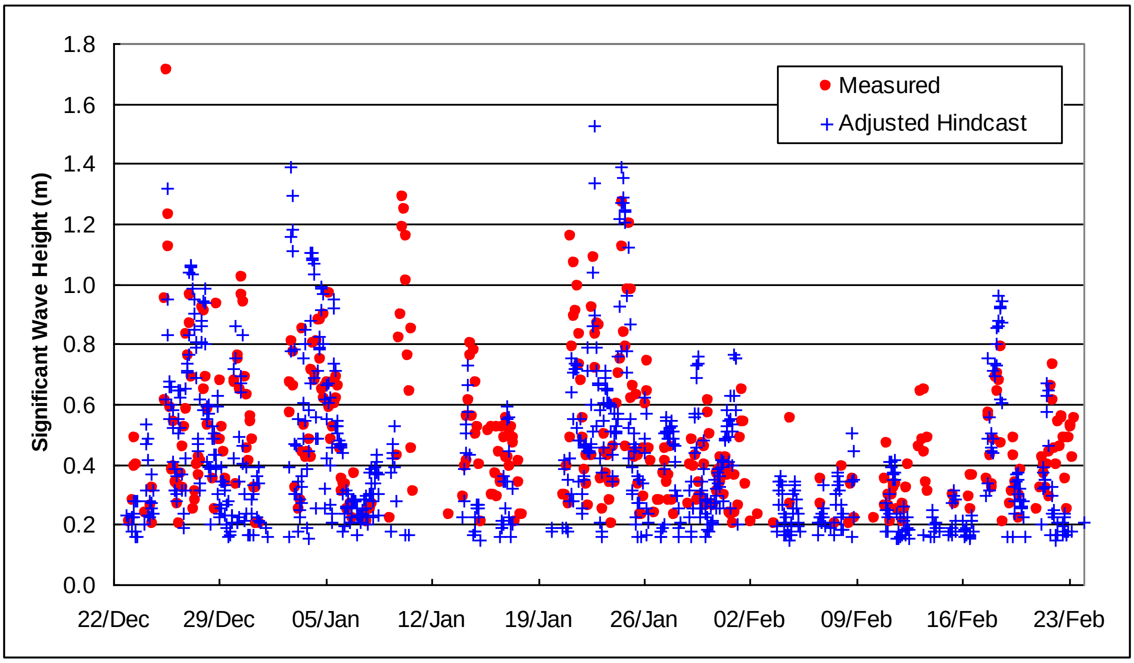

Figure 3-11 Time series of measured (2011-'12) versus adjusted SMB model wave height

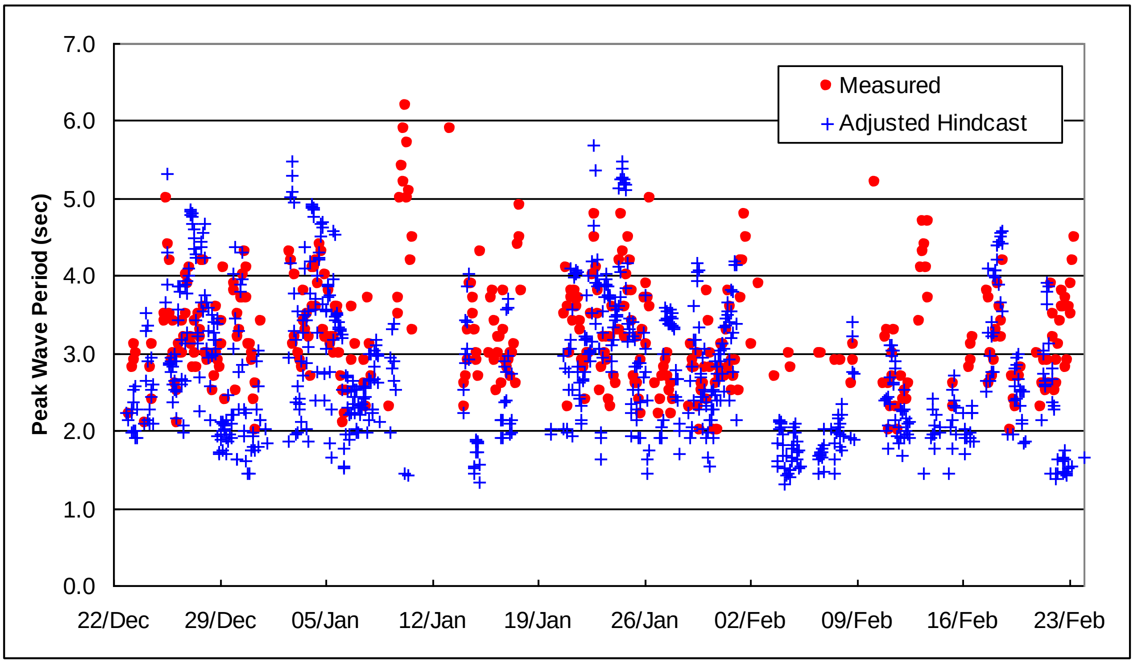

Figure 3-12 Time series of measured (2011-'12) versus adjusted SMB model wave period

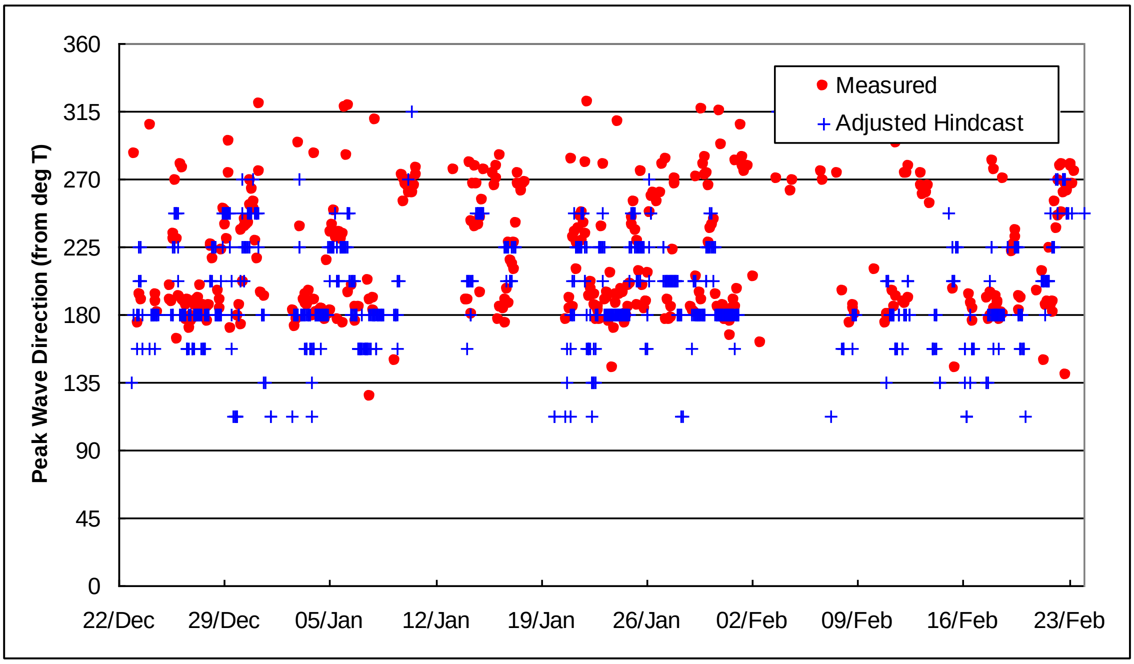

Figure 3-13 Time series of measured (2011-'12) versus adjusted SMB model wave direction

4 Results

4.1 Operational Waves

The wave hindcast for the proposed Gateway Pacific terminal is based on measured winds at Saturna Island from 1 Mar. 1994 to 31 Oct. 2012. The wave heights predicted by the SMB model have been adjusted to more closely match wave measurements made between 22 Dec. 2011 and 23 Feb. 2012. Due to some uncertainty in the wind regime for this area, a marginal level of conservatism has been retained in the hindcast wave heights.

Figure 4-1 shows the wave height statistics derived from the hindcast data. In addition to the full hindcast period, average statistics for the winters (Nov. 1 to Mar. 31) and the spring-summer-fall (Apr. 1 to Oct. 31) are also shown in the plot. Site measurements are included for comparison. As expected, waves at Cherry Point are higher during the Nov. to Mar. period with significant wave heights exceeding 1.0 m for 2% of the time on average in comparison to 0.18% of the time during the rest of the year. The overall average exceedance probability of Hs = 1.0 m is 0.9%, and 0.1% for Hs = 1.4 m.

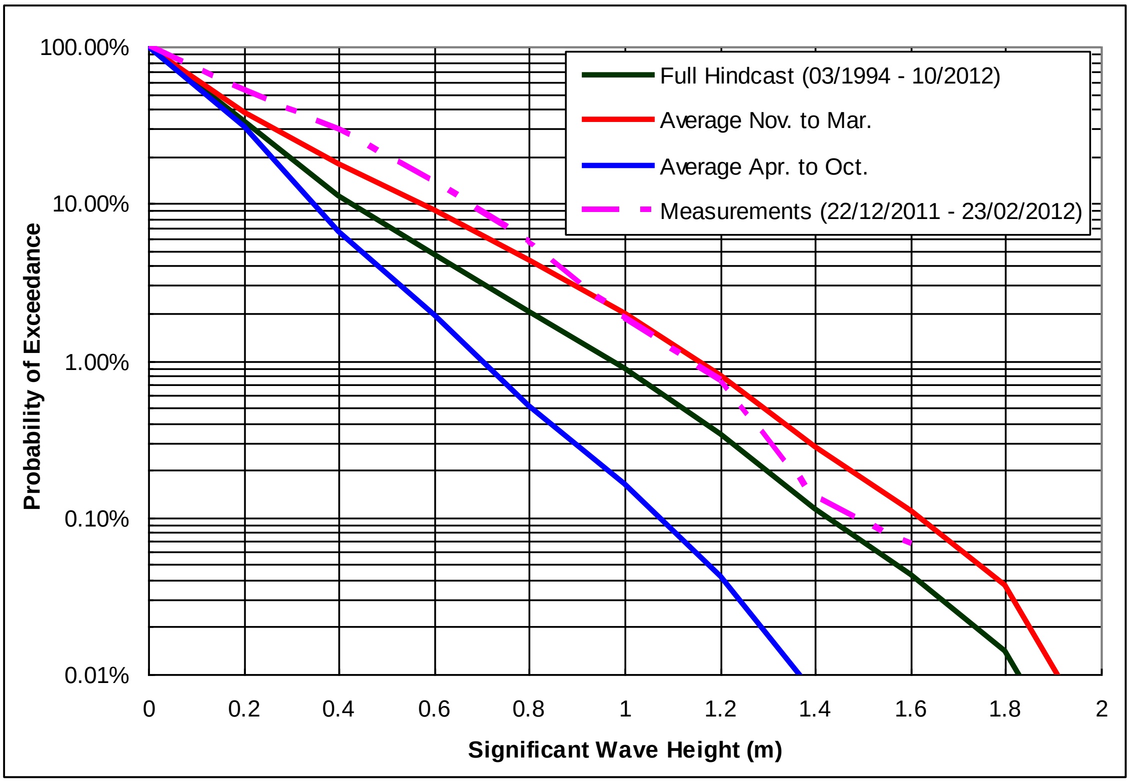

Figure 4-1 Wave height exceedance statistics from Cherry Point hindcast

Figure 4-2 shows the probability of occurrence of peak wave periods for the full hindcast duration, during all the Nov. to Mar. winter periods, and during all the Apr. to Oct. periods. The measured wave periods for the Dec. 2011 to Feb. 2012 period are also shown.

Wave periods are mainly in the 2 sec to 4 sec range. Waves with longer peak periods (5 sec to 7 sec) are seen to occur more often in the winter months. The comparison with the measured wave periods shows that hindcast wave periods are biased marginally lower by 0.5 to 1.0 sec for operational waves and marginally higher by up to 0.5 sec for storm waves.

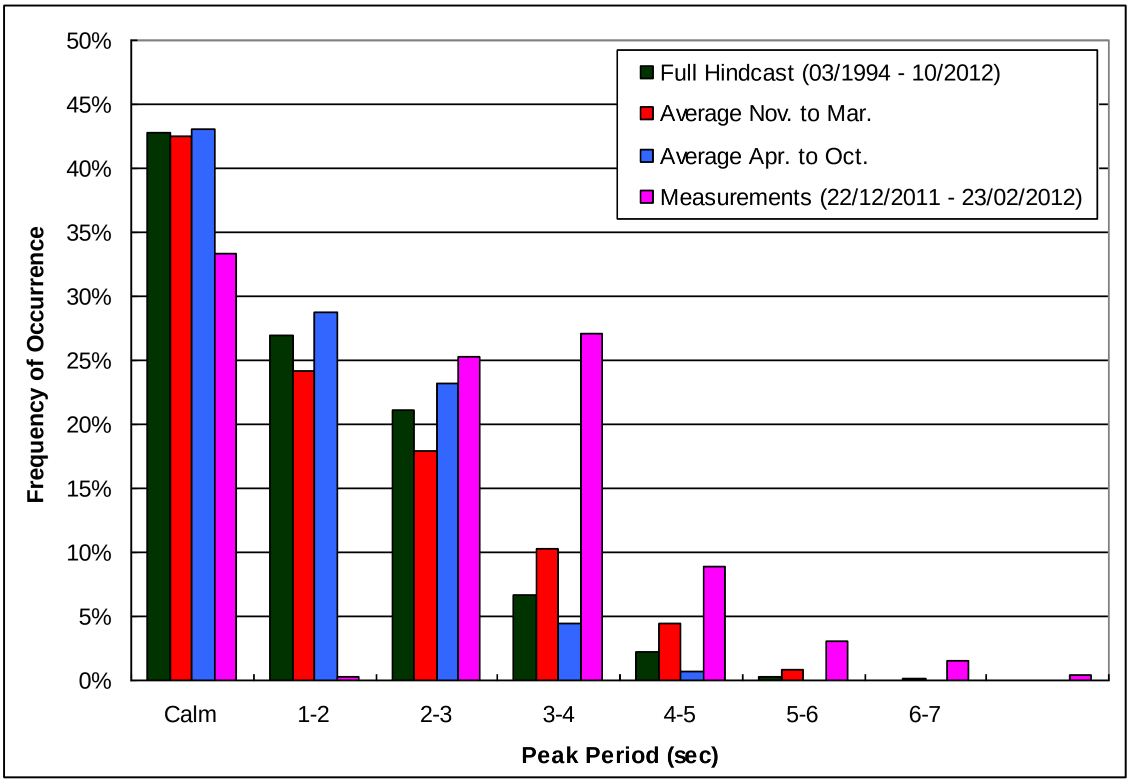

Figure 4-2 Wave period occurrence statistics from Cherry Point hindcast

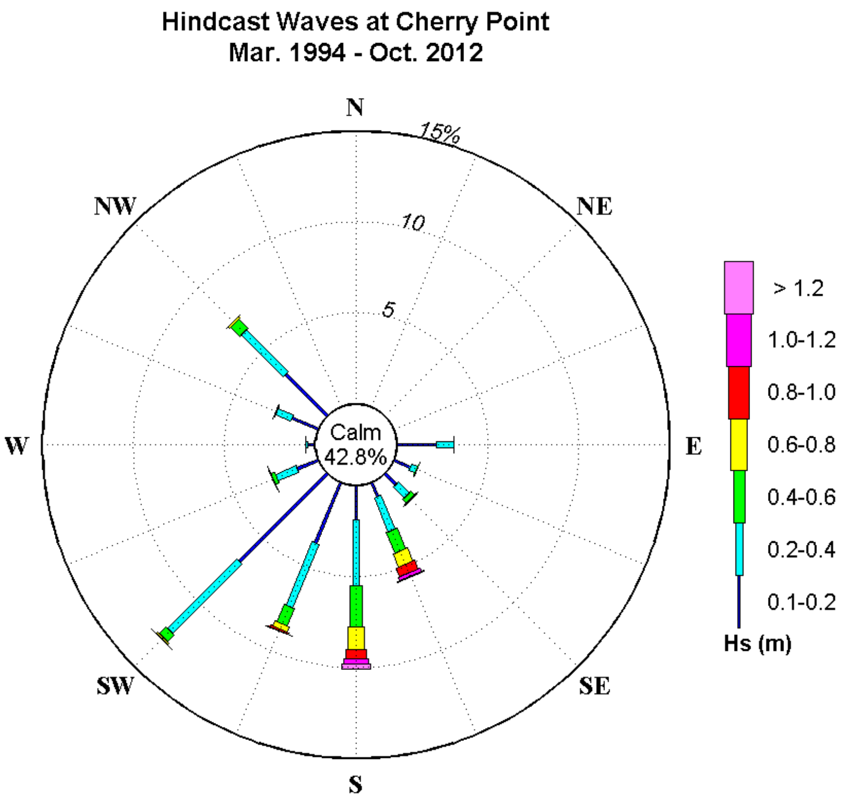

Figure 4-3 Wave rose from Cherry Point hindcast

The wave rose in Figure 4-3 shows that the majority of the incoming wave energy is incident from the southwest sector. The highest waves are predicted from the south and south-southeast direction.

Detailed scatter tables of hindcast wave conditions and measured wind at Cherry Point and Saturna Island are given in Appendix 1.

4.2 Extreme Waves

An analysis of extreme wave heights has been carried out on the time series of hindcast significant wave height at Cherry Point. A Peak-Over-Threshold method with a threshold Hs = 1.5 m is used to identify storm events. To ensure that each event corresponds to an independent storm, a minimum 48 hours between events is specified when selecting events. A total of 35 events over the 17.7 year long (note that data record gaps total to 11.8 months) hindcast dataset have been used in the analysis. A Gumbel probability distribution has been fitted to the maximum Hs value from each storm and the results are shown in Figure 4-4.

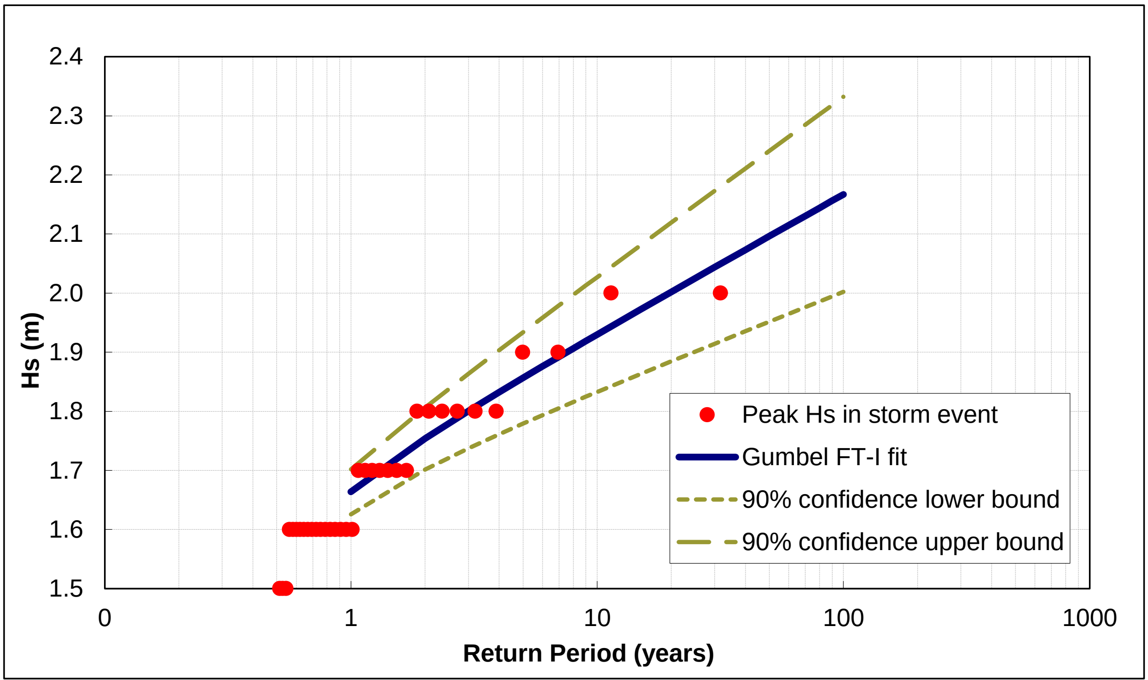

Figure 4-4 Gumbel distribution fit to Cherry Point storm peaks

Table 4-1 Return period wave conditions at Cherry Point berth location

Return Period (yrs)	Hs (m)	Tp (sec)	Dp (deg)
1	1.65	5.9	165 to 195
5	1.86	6.2	
10	1.93	6.3	
20	2.00	6.5	
50	2.10	6.6	
100	2.17	6.7	

The results of the extreme value analysis are given in Table 4-1. The 100 year return period Hs is estimated at 2.17 m. The peak period associated with this wave height is 6.7 sec, and the peak wave direction for this event will lie between 165 and 195 deg.

Alternate extreme value analysis methods using the Generalised Extreme Value (GEV) and Generalised Pareto (GP) distributions yield return period estimates of significant wave height that are marginally (approximately 0.1 m) lower. It is recommended that the values provided in Table 4-1 be used for the design of marine facilities at the proposed berth.

5 Summary

This report presents a study of metocean conditions at the proposed Gateway Pacific terminal in Cherry Point, WA.

5.1 Data Sources

As part of the study, an ADCP instrument was installed at the intended berth location in 22.6 m water depth (referenced to MSL) from 22 Dec. 2011 to 23 Feb. 2012. Data including water level, current profiles and directional wave spectra were obtained from the instrument and analysed.

Wind measurements and water level datum information have also been retrieved from the NOAA-NOS station CHYW1 – 9449424 at Cherry Point. Since the wind data at Cherry Point is available only from Sep. 2008, a longer (17+ years) record of wind measurements from the Environment Canada station on the southeastern tip of Saturna Island has also been obtained.

5.2 Water Level

Statistical analysis of the measured water levels at Cherry Point indicates that the water level with a 1% annual probability of exceedance is 2.29 m above MSL (3.9 m above chart datum). In addition, an allowance of 1 cm for every year of the terminal's design life should be added to the design water level to account for climate change induced sea level rise.

5.3 Currents

The ADCP measurements indicate that currents at the project site mainly flow towards the WNW during the flood and towards ESE during the ebb. Near-surface flood currents typically do not exceed 0.7 m/s (1.4 knots). Peak spring tide ebb current speeds are approximately half of current speeds during the flood.

5.4 Winds

Comparison of the overlapping wind statistics from the two measurement locations shows that the wind regime in the area has significant spatial variability. In general, southerly winds are strongest at both locations, and the Saturna Island instrument records higher speeds. Hourly average wind speeds at Cherry Point are estimated to exceed 8 m/s (15.6 knots) and 12 m/s (23 knots) for approximately 9% and 1% of the time respectively.

5.5 Operational Waves

Waves at the proposed terminal will be locally generated by winds in the southern part of the Strait of Georgia. No open ocean swell is expected to arrive at the site due to the orientation of the Strait of Juan de Fuca and the islands to the southwest of Cherry Point.

A wave hindcast has been completed using a model based on the SMB equations. Wind from Saturna Island measurements along with estimates of open water fetch lengths along several compass directions and average water depth for each fetch have been used as model inputs. The model predictions have been validated against results from a more comprehensive 3rd generation wave model, SWAN. The ADCP measured waves have been used to tune the output of the SMB model.

Statistics of the hindcast waves indicate that a significant wave height of 0.4 m is estimated to be exceeded on average 11.2% of the time at the proposed berth location, and a wave height of 1.0 m exceeded 1% of the time. Peak wave periods mainly lie between 2 sec and 4 sec. The majority of the waves are incident from the southwest quadrant.

The hindcast data indicates that conditions are calm at the proposed berth location (Hs < 0.1 m and/or Tp < 1 sec) for approximately 43% of the time.

5.6 Extreme Waves

Extreme value analysis of storm events selected from the hindcast wave record yields 50 year and 100 year return period estimates of the significant wave height as 2.10 m and 2.17 m respectively. The peak wave period associated with these events is 6.6 sec and 6.7 sec respectively. Severe storms (Hs > 1.5 m) at the project site are all expected to be incident from the south, with a direction range between 166 deg and 195 deg.

6 References

"Current Profile & Wave Measurements, Gateway Pacific Terminal, Cherry Point, WA, Dec 22 2011 – Feb 23 2012", ASL Environmental Sciences Inc., 27 Feb. 2012.

Shore Protection Manual (1984), US Army Corps of Engineers; Coastal Engineering Research Centre.

Appendix 1 – Wind and Wave Scatter Tables (data at 1 hr intervals)

Winds measured at Cherry Point NOAA-NOS station (10 Sep. 2008 to 1 Oct. 2012):

Potential Number of Observations in Specified Time Interval (-): 35592

Actual Number of Valid Observations in Specified Time Interval (-): 35096

Number of Calm Observations in Specified Time Interval (-): 1213

Number of Valid Observations Meeting All Search Criteria (-): 35096

Scatter table of hourly average wind speed versus wind direction

Mean Direction (from deg True)

U (m/s)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total	PDF	CDF
0.0 - 2.0	414	402	393	433	434	612	1232	1475	688	357	284	271	293	414	379	308	8389	23.9%	27.4%
2.0 - 4.0	275	285	491	820	444	359	1504	2452	1190	430	192	208	275	619	655	396	10595	30.2%	57.5%
4.0 - 6.0	38	34	394	1290	176	85	938	1828	888	299	243	109	90	316	400	166	7294	20.8%	78.3%
6.0 - 8.0	1	7	228	1145	53	45	449	1087	348	222	319	103	58	117	140	62	4384	12.5%	90.8%
8.0 - 10.0	0	5	77	516	4	6	160	528	153	114	209	70	42	79	69	10	2042	5.8%	96.6%
10.0 - 12.0	0	5	39	143	0	0	39	245	53	50	83	31	16	59	28	1	792	2.3%	98.9%
12.0 - 14.0	0	2	35	38	0	0	1	111	15	17	24	9	3	15	2	0	272	0.8%	99.7%
14.0 - 16.0	0	0	3	4	0	0	0	52	6	2	3	3	0	5	0	0	78	0.2%	99.9%
16.0 - 18.0	0	0	0	0	0	0	0	21	1	0	1	0	0	0	0	0	23	0.1%	100.0%
18.0 - 20.0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	8	0.0%	100.0%
20.0 - 22.0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	6	0.0%	100.0%
Total	728	740	1660	4389	1111	1107	4323	7813	3342	1491	1358	804	777	1624	1673	943	33883		
PDF	2.1%	2.1%	4.7%	12.5%	3.2%	3.2%	12.3%	22.3%	9.5%	4.2%	3.9%	2.3%	2.2%	4.6%	4.8%	2.7%			
CDF	5.5%	7.6%	12.4%	24.9%	28.0%	31.2%	43.5%	65.8%	75.3%	79.5%	83.4%	85.7%	87.9%	92.5%	97.3%	100.0%			

Notes:

1: Values within bins are >= Lower Bin Limit AND < Upper Bin Limit

2: CDF percentages include calm hours

3: Air is calm if U < 0.5 m/s (1 knot)

Winds measured at Environment Canada Saturna Island CS station (1 Mar. 1994 to 31 Oct. 2012):

Potential Number of Observations in Specified Time Interval (-): 163680

Actual Number of Valid Observations in Specified Time Interval (-): 155174

Number of Calm Observations in Specified Time Interval (-): 1610

Number of Valid Observations Meeting All Search Criteria (-): 155174

Scatter table of hourly average wind speed versus wind direction

Mean Direction (from deg True)

U (m/s)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total	PDF	CDF
0.0 - 2.0	1967	1069	1084	1005	1603	1148	1299	1550	3141	2859	3379	2614	3804	7111	6723	2724	43080	27.8%	28.8%
2.0 - 4.0	1380	792	780	878	1590	955	891	1047	2772	4970	8371	2940	673	2677	5775	2655	39146	25.2%	54.0%
4.0 - 6.0	945	681	806	1102	2202	973	1164	1794	3683	5967	9732	1429	113	347	2086	1818	34842	22.5%	76.5%
6.0 - 8.0	337	275	503	938	1569	587	862	1982	3641	2866	2607	146	6	7	164	359	16849	10.9%	87.3%
8.0 - 10.0	71	93	341	673	884	328	568	1588	2484	1250	628	10	0	0	2	40	8960	5.8%	93.1%
10.0 - 12.0	13	57	242	460	368	146	321	1078	1340	489	207	1	0	0	1	0	4723	3.0%	96.2%
12.0 - 14.0	4	46	206	251	137	74	204	777	771	173	76	1	0	0	0	0	2720	1.8%	97.9%
14.0 - 16.0	2	45	145	149	32	35	116	589	399	68	21	0	0	0	0	0	1601	1.0%	98.9%
16.0 - 18.0	0	16	38	46	8	16	66	341	202	19	6	0	0	0	0	0	758	0.5%	99.4%
18.0 - 20.0	1	7	16	26	4	7	51	250	137	10	1	0	0	0	0	0	510	0.3%	99.8%
20.0 - 22.0	0	0	5	1	0	2	33	121	67	4	2	0	0	0	0	0	235	0.2%	99.9%
22.0 - 24.0	0	0	1	0	1	1	7	50	37	3	0	0	0	0	0	0	100	0.1%	100.0%
24.0 - 26.0	0	0	0	0	0	0	4	15	12	1	0	0	0	0	0	0	32	0.0%	100.0%
26.0 - 28.0	0	0	0	0	0	0	0	6	1	0	0	0	0	0	0	0	7	0.0%	100.0%
28.0 - 30.0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0.0%	100.0%
Total	4720	3081	4167	5529	8398	4272	5586	11189	18687	18679	25030	7141	4596	10142	14751	7596	153564		
PDF	3.0%	2.0%	2.7%	3.6%	5.4%	2.8%	3.6%	7.2%	12.0%	12.0%	16.1%	4.6%	3.0%	6.5%	9.5%	4.9%			
CDF	4.1%	6.1%	8.8%	12.3%	17.7%	20.5%	24.1%	31.3%	43.3%	55.4%	71.5%	76.1%	79.1%	85.6%	95.1%	100.0%			

Notes:

1: Values within bins are >= Lower Bin Limit AND < Upper Bin Limit

2: CDF percentages include calm hours

3: Air is calm if U < 0.5 m/s (1 knot)

Hindcast waves at proposed Gateway Pacific terminal (1 Mar. 1994 to 31 Oct. 2012):

Potential Number of Observations in Specified Time Interval (-): 163680

Actual Number of Valid Observations in Specified Time Interval (-): 155174

Number of Calm Observations in Specified Time Interval (-): 66387

Number of Valid Observations Meeting All Search Criteria (-): 155174

Scatter table of significant wave height versus peak wave direction

Peak Direction (from deg True)

Hs (m)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total	PDF	CDF
0.0 - 0.2	0	0	0	0	3329	1510	1305	1287	2882	5555	10561	1947	635	2475	4996	0	36482	23.5%	66.3%
0.2 - 0.4	0	0	0	0	1536	570	1320	3136	5620	5904	8405	1898	179	1354	5073	0	34995	22.6%	88.8%
0.4 - 0.6	0	0	0	0	26	60	430	1922	3528	1577	786	349	18	126	1096	0	9918	6.4%	95.2%
0.6 - 0.8	0	0	0	0	1	1	98	1214	1930	503	190	66	1	8	190	0	4202	2.7%	97.9%
0.8 - 1.0	0	0	0	0	0	0	8	781	835	141	41	1	0	0	6	0	1813	1.2%	99.1%
1.0 - 1.2	0	0	0	0	0	0	0	329	464	49	10	2	0	0	0	0	854	0.6%	99.7%
1.2 - 1.4	0	0	0	0	0	0	0	100	229	15	1	1	0	0	0	0	346	0.2%	99.9%
1.4 - 1.6	0	0	0	0	0	0	0	12	94	3	1	0	0	0	0	0	110	0.1%	100.0%
1.6 - 1.8	0	0	0	0	0	0	0	2	38	5	0	0	0	0	0	0	45	0.0%	100.0%
1.8 - 2.0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	20	0.0%	100.0%
2.0 - 2.2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0.0%	100.0%
Total	0	0	0	0	4892	2141	3161	8783	15642	13752	19995	4264	833	3963	11361	0	88787		
PDF	0.0%	0.0%	0.0%	0.0%	3.2%	1.4%	2.0%	5.7%	10.1%	8.9%	12.9%	2.7%	0.5%	2.6%	7.3%	0.0%			
CDF	42.8%	42.8%	42.8%	42.8%	45.9%	47.3%	49.4%	55.0%	65.1%	74.0%	86.8%	89.6%	90.1%	92.7%	100.0%	100.0%			

Notes:

1: Values within bins are >= Lower Bin Limit AND < Upper Bin Limit

2: CDF percentages include calm hours

3: Sea is calm if Hs < 0.1 m OR Tp < 1.0 sec

Hindcast waves at proposed Gateway Pacific terminal (1 Mar. 1994 to 31 Oct. 2012):

Potential Number of Observations in Specified Time Interval (-): 163680

Actual Number of Valid Observations in Specified Time Interval (-): 155174

Number of Calm Observations in Specified Time Interval (-): 66387

Number of Valid Observations Meeting All Search Criteria (-): 155174

Scatter table of significant wave height versus peak wave period

	Peak Spectral Period (s)									
Hs (m)	0.0 - 1.0	1.0 - 2.0	2.0 - 3.0	3.0 - 4.0	4.0 - 5.0	5.0 - 6.0	6.0 - 7.0	Total	PDF	CDF
0.0 - 0.2	0	32748	3734	0	0	0	0	36482	23.5%	66.3%
0.2 - 0.4	0	9008	25656	331	0	0	0	34995	22.6%	88.8%
0.4 - 0.6	0	33	3095	6790	0	0	0	9918	6.4%	95.2%
0.6 - 0.8	0	0	245	3047	910	0	0	4202	2.7%	97.9%
0.8 - 1.0	0	0	0	169	1644	0	0	1813	1.2%	99.1%
1.0 - 1.2	0	0	0	28	730	96	0	854	0.6%	99.7%
1.2 - 1.4	0	0	0	1	71	274	0	346	0.2%	99.9%
1.4 - 1.6	0	0	0	0	7	103	0	110	0.1%	100.0%
1.6 - 1.8	0	0	0	0	0	30	15	45	0.0%	100.0%
1.8 - 2.0	0	0	0	0	0	0	20	20	0.0%	100.0%
2.0 - 2.2	0	0	0	0	0	0	2	2	0.0%	100.0%
Total	0	41789	32730	10366	3362	503	37	88787		
PDF	0.0%	26.9%	21.1%	6.7%	2.2%	0.3%	0.0%			
CDF	42.8%	69.7%	90.8%	97.5%	99.7%	100.0%	100.0%			

Notes:

1: Values within bins are >= Lower Bin Limit AND < Upper Bin Limit

2: CDF percentages include calm hours

3: Sea is calm if Hs < 0.1 m OR Tp < 1.0 sec

Hindcast waves at proposed Gateway Pacific terminal (1 Mar. 1994 to 31 Oct. 2012):

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Actual Number of Valid Observations in Specified Time Interval (-): 155174

Number of Calm Observations in Specified Time Interval (-): 66387

Number of Valid Observations Meeting All Search Criteria (-): 155174

Scatter table of peak wave period versus peak wave direction

	Peak Direction (from deg True)																		
Tp (s)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total	PDF	CDF
0.0 - 1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%	42.8%
1.0 - 2.0	0	0	0	0	4389	1401	1213	1327	2921	4901	8670	3477	789	3601	9100	0	41789	26.9%	69.7%
2.0 - 3.0	0	0	0	0	503	726	1641	3382	5971	6805	10283	775	44	360	2240	0	32730	21.1%	90.8%
3.0 - 4.0	0	0	0	0	0	14	307	2710	4609	1747	944	12	0	2	21	0	10366	6.7%	97.5%
4.0 - 5.0	0	0	0	0	0	0	0	1317	1670	277	98	0	0	0	0	0	3362	2.2%	99.7%
5.0 - 6.0	0	0	0	0	0	0	0	47	436	20	0	0	0	0	0	0	503	0.3%	100.0%
6.0 - 7.0	0	0	0	0	0	0	0	0	35	2	0	0	0	0	0	0	37	0.0%	100.0%
Total	0	0	0	0	4892	2141	3161	8783	15642	13752	19995	4264	833	3963	11361	0	88787		
PDF	0.0%	0.0%	0.0%	0.0%	3.2%	1.4%	2.0%	5.7%	10.1%	8.9%	12.9%	2.7%	0.5%	2.6%	7.3%	0.0%			
CDF	42.8%	42.8%	42.8%	42.8%	45.9%	47.3%	49.4%	55.0%	65.1%	74.0%	86.8%	89.6%	90.1%	92.7%	100.0%	100.0%			

Notes:

1: Values within bins are >= Lower Bin Limit AND < Upper Bin Limit

2: CDF percentages include calm hours

3: Sea is calm if Hs < 0.1 m OR Tp < 1.0 sec